

Effect of mode shift from car to light rail on personal exposure: A controlled experiment

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Abstract

Light rail transit (LRT) has a reputation for being cleaner and healthier than automobiles. However, few studies have examined the effects of mode shift from automobile to LRT. This paper investigates to what extent mode shift from car to LRT can reduce personal exposure to PM_{2.5}, BC, and UFP. Simultaneous measurements on LRT and automobile were conducted under four plausible commuting scenarios in Los Angeles, California from October to November in 2014. As a robustness check, Monte Carlo simulations were performed to test the effects of confounding factors. Under the closed ventilation and low traffic condition, personal exposure measurements inside LRT were significantly higher than in automobile for BC (+40%, $p < 0.01$) and UFP (+27%, $p < 0.01$). However, under the open ventilation and high traffic condition, personal exposure was significantly lower in LRT than in automobile for PM_{2.5} (-38%, $p < 0.01$); BC (-68%, $p < 0.01$); and UFP (-141%, $p < 0.01$). Results of the Monte Carlo simulations suggest that other factors, such as vehicle fan strength, vehicle speed, and vehicle age, appear to have marginal effects on personal exposure. These results demonstrate that the effect of mode shift from car to LRT can be significantly altered by ventilation settings and travel route choices. Results inform future research and policy about the importance of incorporating ventilation and traffic microenvironments for assessing the health effects of a mode switch from car to LRT.

Highlights

- Examined the effect of mode shift from car to LRT using simultaneous measurements
- Developed Monte Carlo simulations to test the effects of confounding factors
- The effect of mode shift was driven by ventilation and traffic condition
- Other factors, such as vehicle age, speed, and fan strength, were less influential

Keywords: mode shift; personal exposure; simultaneous measurement; Monte Carlo simulation; ventilation; microenvironment

1. INTRODUCTION

Light rail transit (LRT) has a long-standing reputation as a clean and healthy transportation. It has been generally known that LRT offers intermediate health benefits in terms of physical activity (Brown et al., 2015; Hong et al., 2016) and air quality (Chen and Whalley, 2012; Saxe et al., 2015). When it comes to air pollution, transportation literature often reports that electricity-powered rail system contributes to reducing traffic emissions because it consumes less energy and generates less emissions per passenger kilometer compared to automobiles (TRB, 2011). When it comes to air pollution exposure, however, benefits of LRT over automobiles remain less clear, with mixed results reported in the literature (Morabia et al., 2010; Zuurbier et al., 2010).

Previous studies of commuter exposure can be broadly defined into two groups: i) multi modal studies that compare exposure differences across multiple travel modes; and ii) single mode studies that focus on exposure assessment of a specific travel mode. Multi modal studies have generally shown that active travel modes have higher exposure than less active modes (Kaur et al., 2005). However, a growing body of research suggests that modal difference alone may not fully explain the difference in personal exposure (Ham et al., 2017; Kaur et al., 2007; Knibbs et al., 2011). Differences caused by a specific mode can be trumped by other factors, such as ventilation and traffic microenvironments. Especially, ventilation setting of a vehicle could be a deciding factor because personal exposure is largely influenced by how much outside pollutants penetrate into the vehicle (Chaney et al., 2017; Ham et al., 2017; Quiros et al., 2013).

On the other hand, single mode studies offer more nuanced understanding of the mechanism by which modal differences might affect air pollution exposure. For example, in-vehicle exposure studies suggest that pollutant concentrations inside vehicles can be highly variable (Fruin et al., 2011). Even for the same type of vehicle, in-vehicle exposure may differ significantly depending on ventilation settings, roadway types, traffic condition, and vehicle and driving characteristics (Fruin et al., 2011; Hudda et al., 2012; Knibbs et al., 2009; Ott et al., 2008). Previous studies of in-vehicle exposure indicate that both on-road concentrations and penetration rates of outside pollutants into vehicles are equally important factors (Hudda et al., 2012; Knibbs et al., 2010). Therefore, an accurate assessment of in-vehicle exposures would require the consideration of key factors related to driver and vehicle characteristics as well as transport microenvironments.

Notably, few empirical studies have systemically examined the effects of mode shift from car to rail transit on air pollution exposure. One study from Salt Lake, Utah conducted simultaneous measurements of PM_{2.5} while taking into account different driving conditions with closed/open windows (Chaney et al., 2017). A recent study from Sacramento, California has conducted a large-scale multi modal exposure assessment and found ventilation settings to have a significant effect on personal exposure (Ham et al., 2017). Most of the previous studies, however, have focused on the effect of a mode shift from car to active transportation, such as walking and biking (Mueller et al., 2015; Rabl and de Nazelle, 2012). Although potential gains in physical activity may be greater from switching to active travel, it would be more practical to focus on encouraging auto drivers to switch to rail transit. From a public policy point of view, rail transit has a larger contribution to an urban mode share and ridership potential than active transport modes in many urban areas.

To fill this important gap, this study investigates the effect of mode shift from automobile to light rail transit (LRT) on personal air pollution exposure. A paired set of personal exposure monitoring instruments was employed to simultaneously measure and compare in-vehicle concentrations and in-LRT concentrations under four plausible commuting scenarios. The simultaneous measurement allowed us to control for daily variations in meteorological condition and background ambient concentrations. To the best of our knowledge, this is one of the first studies to systematically investigate the effect of mode shift from automobile to LRT using simultaneous measurements under four commuting scenarios with varying conditions of ventilation settings and traffic microenvironments.

2. MATERIAL AND METHODS

2.1. Research design

The main objective of this study was to assess the effect of mode shift from automobile to LRT on personal air pollution exposure under real-world conditions. To achieve this objective, the study was designed around *three key assumptions*: (1) LRT commuters have relatively consistent

personal exposure levels due to traveling in a temperature-controlled transit environment on a fixed route; (2) the effect of switching from automobile to LRT on air pollution exposure is mainly driven by differences in commuter behavior, in particular, ventilation preference and travel route choice; and (3) personal exposure inside of a car and an LRT can be compared using a carefully designed controlled experiment. It should be noted that ambient concentration levels outside of a vehicle or an LRT can be considerably more variable than the concentration levels inside. Ambient concentrations outside of a car and an LRT could be driven by factors unrelated to fleet characteristics or transit microenvironments, such as exposure to cigarette smoking while waiting on a train platform. Therefore, the focus of this study was to understand the effect of a mode shift on in-vehicle and in-LRT exposures.

Under these assumptions, four hypotheses were formulated to test the effect of ventilation and travel route choice. First, it was hypothesized that taking an LRT would yield higher exposure than driving a car under a closed ventilation setting in low traffic condition (Figure 1(1)). This hypothesis was tested by comparing personal exposure while taking an LRT and driving a car with all windows closed and air recirculating (RC) mode on local streets. Local roads were defined as typical neighborhood streets with an annual average daily traffic (AADT) of less than 50,000, avoiding state and federal highways. Second, it was posited that riding an LRT would yield higher exposure than driving a car under a closed ventilation setting in high traffic condition (Figure 1(2)). This hypothesis was tested by comparing personal exposure while taking an LRT and driving a vehicle on highways (AADT more than 50,000) with RC mode and all windows closed. Third, it was assumed that taking a transit would yield lower exposure than driving a car under an open ventilation setting in low traffic condition (Figure 1(3)). This hypothesis was tested by measuring personal exposure while taking an LRT and driving a vehicle on local streets with windows half open on the driver's seats. Lastly, it was hypothesized that transit use would yield lower exposure than car driving under an open ventilation in high traffic condition (Figure 1(4)). This hypothesis was examined by comparing personal exposure while taking an LRT and driving a car on highways with the driver's side windows half open.

Based on these hypotheses, four experimental conditions were developed, and each sampling session was carried out by randomly selecting one of the four experimental conditions (Figure 1).

The number of sample run was the same across the experimental conditions—10 daily samples per mode per experimental condition, yielding a total of 80 daily samples (see Table S1 for the actual sampling schedule). For the field measurements, the technicians were instructed to keep a time-stamped field note using a smartphone app to record any deviation from the specified experiment condition for that sampling session. The field notes were later synchronized with the field measurements using the timestamp, and only the relevant samples were extracted to match the intended experimental condition, minimizing any measurement errors arising from misclassification. For example, for the second hypothesis (a closed ventilation, high traffic condition scenario), only the measurements taken during traveling along highways and expressways were included while any measurements taken outside of the specified sampling condition were excluded from the final sample. For the in-LRT measurement, the fieldnote was also used to exclude any time spent outside of train, e.g., waiting on a train platform. The coding scheme was manually checked against each experimental condition using the video footages and the GPS trajectories simultaneously obtained during the sampling campaign.

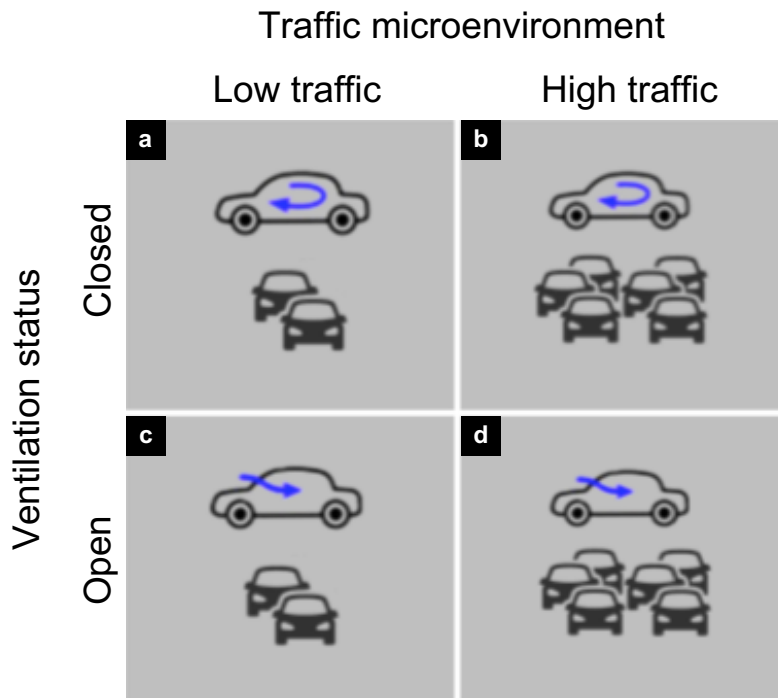


Figure 1. Four plausible commuting scenarios

Note: a) Condition 1: closed ventilation, low traffic; b) Condition 2: closed ventilation, high traffic; c) Condition 3: open ventilation, low traffic; d) Condition 4: open ventilation, high traffic.

As a robustness check, Monte Carlo simulations were conducted to test the effects of other vehicle-specific factors, including fan strength, vehicle speed, and vehicle age. Overall, it was posited that ventilation conditions and traffic microenvironments will play the key role in determining the modal difference in traffic exposure between car and LRT.

2.2. Site location and sampling route description

Figure 2 shows the two sampling routes selected for this study. The vehicle and transit routes were carefully selected to represent different transport microenvironments for urban commuters. The vehicle route consists of three highways (I-10, I-110, and I-210) or local streets connecting Culver City and Pasadena. Highway I-10 is the major east-west corridor that connects Los Angeles to Santa Monica, with a daily traffic volume reaching 280,000 vehicles. I-110 is one of the busiest highways in the US with a traffic volume reaching over 328,000 vehicles per day. I-210 is also heavily trafficked highways with a traffic volume reaching 298,000 vehicles per day. I-210 is the major east-west corridor that connects Los Angeles and San Bernardino. The vehicle route also includes local streets that run parallel to the highway route, except that they are typically four-lane local roads. The train route was similar to the vehicle route, consisting of three lines of the Los Angeles Metro system (Expo, Red/Purple, and Gold lines). The Expo line is a ground-level light rail transit system connecting downtown Los Angeles to Culver City, eventually reaching downtown Santa Monica in 2016. The Red/Purple line is an underground subway system that connects downtown Los Angeles to North Hollywood. The Gold line is also a ground-level light rail system connecting downtown Los Angeles to Pasadena and to East Los Angeles.

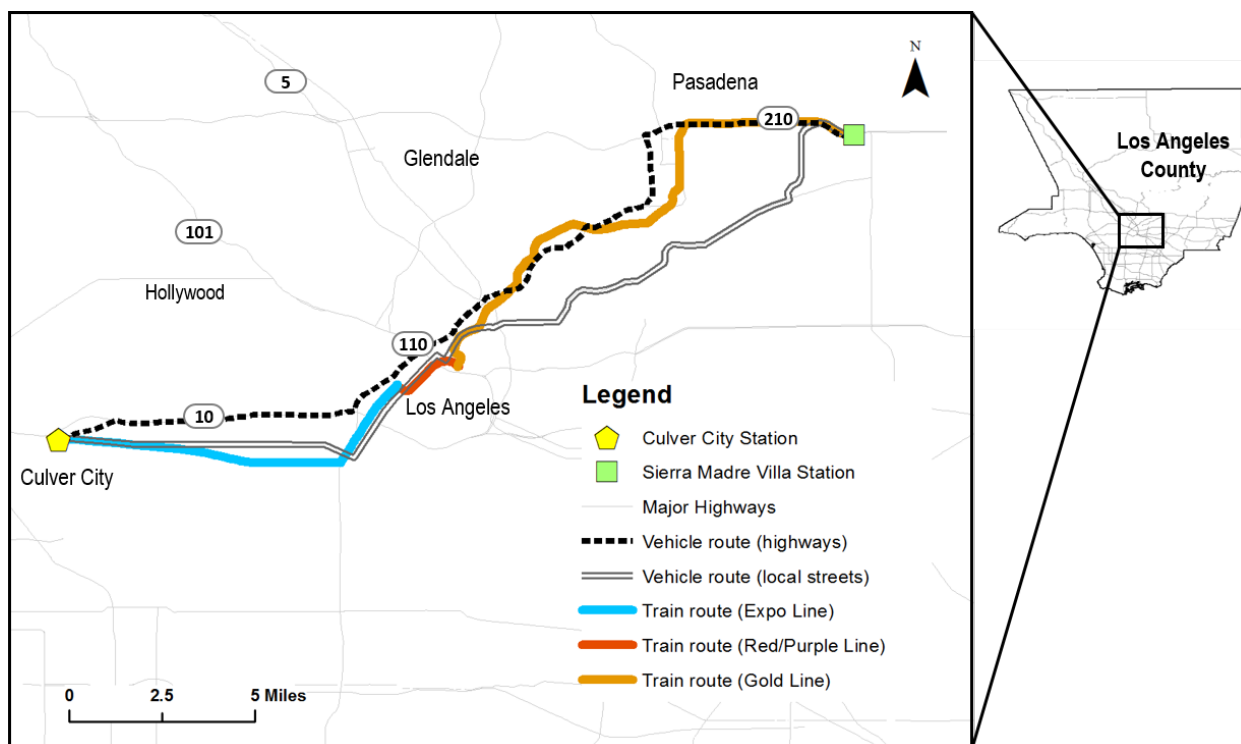


Figure 2. Map of sampling routes

2.3. Study protocol and validation

For the field measurement, two trained technicians simultaneously collected pollutant samples on weekdays from October 13 through November 14, 2014, resulting in over 803 hours of samples (a total of 80 one-way trips). For each daily sampling campaign, two sampling sessions were carried out, consisting of a forward trip from the Culver City Station to the Sierra Madre Villa Station in Pasadena and a backward trip from the Sierra Madre Villa Station to the Culver City Station (Figure 2). Along the sampling routes, one technician drove the car and the other technician took the LRT train simultaneously from 7:00 am through 12:00 pm. The driving route consists of various local streets and three highways (I-10, I-110, and I-210). LRT route consists of two Metro lines: the Expo line and the Gold line. The Red/Purple lines were excluded from the study due to a significantly different environment of subway systems. As is typical with Metro at this time of the year, the transit system was always air conditioned, except for when the train reached the terminal station.

To ensure the validity of the study protocol, a visual survey was conducted to determine whether our experimental conditions reflect the real driving conditions in Los Angeles. Based on the spot visual survey of vehicles via video recordings (Figure S1), it was confirmed that more than one third of the vehicles had their driver's side windows opened at least in half, despite a high ambient temperature (about 30 °C) during the spot survey.

In addition, a pilot sampling was conducted using portable Aethalometers (AE51, Aethlab™). The pilot measurement indicated that sampling in the morning proved to be more effective in demonstrating differences between the travel modes. Afternoon pollutant concentrations showed little or no differences between the travel modes (Figure S2). This difference can be explained by a combination of lower mixing height and more intense anthropogenic activities in the morning than in the afternoon, a phenomenon commonly known as the 'diurnal effect' (Oke, 1988). The pilot study also confirmed that the ventilation setting offered two contrasting experimental conditions – one that gives the maximum air exchange rate (AER) close to 80 – 120 h⁻¹ (open-window), and another that gives the minimum air exchange rate close to 3.5 – 9.5 h⁻¹ (closed-window).

2.4. Instrumentation

Table 1 provides a summary of the instruments used in this study. Two Condensation Particle Counters (CPCs) were employed to measure ultrafine particle (UFP) inside the vehicle and the rail transit cabin (Figure S3). The TSI's CPC 3007 is a handheld device that measures the number of particle size 0.01 – 1 μm. This device uses isopropanol as a condensing liquid and can be operated up to 6 hours with one fill-up. For each sampling session, a trained lab technician tested the flow rates of CPCs and performed a zero-check with a high efficiency particulate air filter (HEPA) on a daily basis.

Table 1. Summary of instruments used in the study

Device	Manufacturer	Measures	Time resolution
CPC 3007	TSI Inc., MN, USA	Particle count, 10 nm - 1 μm	10 secs
SidePak AM510	TSI Inc., MN, USA	PM _{2.5} mass concentration	30 secs
Q-trak	TSI Inc., MN, USA	CO, CO ₂ , temp, humidity	5 secs

AE-51 Aethalometer	AethLab CA, USA	BC mass concentration	1 min
BT-Q1000XT	Qstarz, Taipei, Taiwan	Location (latitude, longitude)	1 sec
SJ4000	SJCAM, Shenzhen, China	Video footage	continuous
Smartphone	Neukadye Timestamped Filed Notes	Unusual events	n/a

Two SidePak AM510 units measured concentrations of particulate matter $\leq 2.5 \mu\text{m}$ in aerodynamic diameter ($\text{PM}_{2.5}$) inside the vehicle and the rail transit cabin. The TSI's SidePak is a portable photometric aerosol monitor that uses light scattering method to quantify the airborne concentration of particulate matter size 1.0, 2.5, and $10 \mu\text{m}$. The SidePaks were fitted with a $2.5 \mu\text{m}$ impactor to control the cut-off size of particles entering the device. A trained lab technician cleaned the impactor and applied new grease after each sampling session. Prior to each sampling session, the SidePak was zero calibrated with the included HEPA filter, and the flow rate was always set to 1.7 L/min. Because the SidePak devices were factory-calibrated using A1 test dust (Arizona road dust), the actual particles in the air may differ in size, shape, and reflective index. Therefore, a calibration factor of 0.29 was applied for post-processing to reflect the actual $\text{PM}_{2.5}$ particle concentrations. This calibration factor was derived from the previous studies by Lee et al (2007), Jiang et al (2011), and Ott et al (2014) who used a calibration factor of 0.29 for a SidePak monitoring of outdoor aerosols based on a gravimetric comparison.

Two portable Aethalometers (AE51, AethlabTM) were used to measure black carbon concentrations. Aethalometer detects changes in the optical absorption of light transmitted through accumulated black carbon particles captured on a quartz-fiber filter. The air is continuously pumped into the devices, and the devices record concentration levels of black carbon content present in the outside of the vehicle and the transit cabin. The flow rate was always set to 150 ml/min, $\text{ATN} < 50$. All the devices were updated with the latest Firmware version 706. The AE51 is susceptible to shocks and vibrations, and the measurement can be biased for short sample lengths. Thus, a 1-minute sample interval was selected to minimize biases from noisy data.

Other devices used in this study include a TSI's Q-trak, a GPS, and a portable video camera. Q-trak devices were used to measure CO_2 , temperature, and humidity. CO_2 was measured as a

tracer gas to determine whether the field technicians were inside or outside the car and the transit cabin. The GPS devices (Qstarz BT-Q1000XT) were used to determine the locational information of the technicians while driving the car and taking the LRT. The GPS data were lost during the time when the technicians was taking the subway and inside the underground stations. However, the lost data account for less than 5% of the GPS data recorded for each sampling session. To record any unusual events, two portable video cameras (SJCAM SJ4000) were mounted inside the car and clipped on the backpack of the technician. Smartphone-based field note application (Neukadye Time-stamped Filed Notes) was also employed to record starting/ending time and any unusual events. For each sampling campaign, all the devices including the monitoring instruments were synchronized according to the technicians' wristwatch to match the timestamp.

2.5. Data post-processing and instrument validation

All the raw measurements were carefully post-processed based on a set of procedures (See Section S4 for more detail). In brief, PM_{2.5} measurements were corrected for biases affected by ambient relative humidity. Light-scattering based nephelometers generally overestimate PM_{2.5} mass concentrations at higher relative humidity (McMurry et al., 1996). Thus, a correction method used in the previous research (Chakrabarti et al., 2004; Ramachandran et al., 2003) was applied to adjust for the effect of relative humidity on the PM_{2.5} measurements (Figure S5). BC measurements were post-processed using the Optical Noise-reduction Averaging algorithm developed by Hagler (2011) to dynamically reduce any erroneous readings due to presence of optical and electronic noises (Figure S6). MicroAeth device also tends to underestimate measurement with increased filter loading (Jimenez et al., 2007; Kirchstetter and Novakov, 2007). Thus, the loading effect of the BC measurement was corrected using the empirical function developed by Kirchstetter and Novakov (2007) to reduce the bias introduced when sampling highly light-absorbing particles (Figure S7). Lastly, UFP number concentrations were post-processed to reduce any biases arising from particle coincidence effects (more than one particle in the optical scattering volume at a time) when the number concentrations exceed 100,000 #/cm³ (Figure S8) (Westerdahl et al., 2005).

To ensure comparability between the measurements for each instrument pair, all the monitoring instruments were collocated for about 30 minutes before and after each sampling campaign. The

instruments were placed on a passenger seat of the technician's vehicle side by side while driving in a normal condition with open-windows. The measurement was taken while the vehicle was driven to and from the daily starting position (a parking lot of the light rail transit station at Culver City), providing a wide range of instrument readings for robust inter-comparison. The collocated measurements were compared using a correlation function, and showed generally high correlations between the two units for all the instrument pairs (Figure S9). The correlations were stronger for the BC and UFP measurements ($R^2 = 0.96$ and 0.97 , respectively) than the correlations for the $PM_{2.5}$ and CO_2 measurements ($R^2 = 0.93$ and 0.94 , respectively). Note that instrument bias have been observed between portable monitors in the past (Matson et al., 2004), and the manufacturer confirmed that the acceptable difference between the two identical units is within 20%. Although the difference between our instruments was within this margin of error, a linear correlation equation was applied to further correct the readings of one instrument compared to another instrument in order to minimize any potential instrument bias and to allow direct comparison of the measurements conducted while driving a car and taking an LRT.

2.6. Data analysis and robustness check

To compare difference in the measurements between the car and the LRT, the Wilcoxon's signed ranks test was performed. The Wilcoxon's test is a nonparametric test and was preferred over a parametric test (e.g. t -test) because of the non-normal distribution of the pollutant samples. In addition, an ANOVA was used to compare the effects of the experimental conditions on the difference (Δ) in measurements between the paired instruments. The differencing technique was employed in order to minimize daily variations caused by changing meteorological conditions. For example, $\Delta PM_{2.5}$ was calculated by subtracting the in-vehicle $PM_{2.5}$ from the in-LRT $PM_{2.5}$ for each trip. Therefore, the sign of the Δ represents either the increase (+) or the decrease (-) in air pollution exposure when switching from car to LRT. The absolute value of the Δ represents the magnitude of change in air pollution exposure when switching from car to LRT.

Because this study employed one vehicle, 2006 Ford Focus ST, a robustness check was conducted to test if the results would hold the same for other vehicle types and fleet characteristics. Previous studies have shown that vehicle age, fan strength, and vehicle speed, largely influence in-vehicle exposure (Fruin et al., 2011; Hudda et al., 2012, 2011). Therefore, a

series of Monte Carlo simulations was performed to test the effects of other vehicle-specific parameters on in-vehicle air pollution exposure in comparison to in-LRT exposure.

3. RESULTS

3.1. Measured concentration

Table 2 shows the descriptive summary of the measured concentrations for PM_{2.5}, BC, UFP, and CO₂. For PM_{2.5}, no significant difference was observed under the closed ventilation setting (conditions 1 and 2). However, under the open ventilation setting (conditions 3 and 4), in-LRT PM_{2.5} exposure was 38 to 40% lower than in-vehicle exposure ($p < 0.001$). Under the closed ventilation setting, in-LRT BC exposure was 40% higher than in-vehicle exposure (condition 1, $p < 0.01$). However, in-LRT BC exposure was 43% to 68% lower than in-vehicle exposure under the open ventilation setting (conditions 3 and 4, $p < 0.01$). Similarly, under the closed ventilation setting, in-LRT UFP exposure was 27% higher (condition 1, $p < 0.05$). Under the open ventilation setting, however, in-LRT UFP exposure was 78% (condition 3, $p < 0.01$) to 141% higher (condition 4, $p < 0.01$) compared to in-vehicle UFP exposure. For CO₂, the results were opposite from the results of the above three pollutants. Under the closed ventilation setting (conditions 1 and 2), in-LRT CO₂ exposure was lower than in-vehicle exposure. On the other hand, in-LRT CO₂ exposure was higher than in-vehicle exposure under the open ventilation setting (conditions 3 and 4).

Table 2. Descriptive summary of the pollutant measurements

Variable	Experimental condition	LRT				Car				%Δ	<i>p</i>
		Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max		
PM _{2.5} (μg/m ³)	Condition 1	28.75 (17.38)	22.76	10.22	157.27	23.61 (9.93)	20.01	10.18	76.71	18%	—
	Condition 2	31.09 (17.92)	27.32	6.78	96.26	27.1 (8.88)	26.36	10.05	74.47	13%	—
	Condition 3	39.13 (15.93)	37.36	13.98	100.81	54.88 (20.14)	56.87	15.12	124.66	-40%	***
	Condition 4	29.81 (21.81)	24.49	6.78	270.32	41.2 (18.25)	40.51	6.94	101.35	-38%	***
BC (μg/m ³)	Condition 1	2.69 (1.63)	2.58	0.34	9.74	1.61 (0.9)	1.84	0.16	4.4	40%	***
	Condition 2	2.57 (1.67)	2.22	0.22	12.69	2.02 (1.16)	1.65	0.35	5.99	21%	—

	Condition 3	1.98 (1.47)	1.77	0.27	11.21	2.83 (2.22)	2.04	0.58	31.95	-43%	***
	Condition 4	1.8 (1.14)	1.68	0.18	12.24	3.02 (2.07)	2.81	0.55	22.66	-68%	***
UFP (#/cm ³)	Condition 1	23223 (9302)	20286	9299	86590	17001 (13399)	14390	994	145900	27%	**
	Condition 2	22808 (10252)	20923	8396	85183	21791 (11407)	19943	1860	104621	4%	—
	Condition 3	18833 (8726)	17194	8854	119978	33456 (29009)	24028	5892	487258	-78%	***
	Condition 4	21674 (8313)	20257	9219	88685	52271 (41299)	41399	7539	571277	-141%	***
CO ₂ (ppb)	Condition 1	880 (271)	866	458	1773	1949 (797)	1813	701	4033	-121%	***
	Condition 2	828 (227)	776	428	1558	1814 (776)	1506	759	3652	-119%	***
	Condition 3	788 (170)	721	451	1551	530 (83)	523	422	1117	33%	***
	Condition 4	762 (176)	839	428	1315	566 (80)	573	431	1548	26%	***

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic. *P*-values were calculated using Wilcoxon's signed ranks test.

* *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001

Figure 3 through Figure 6 show the boxplots and the probability density plots for each of the experimental conditions. As shown in the probability density plots (panels in the second row) in Figure 3, in-LRT PM_{2.5} exposures showed less variance than in-vehicle PM_{2.5} exposures. Under the closed ventilation setting, the mean difference in PM_{2.5} exposure between LRT and car was small. However, the mean difference becomes larger under the open ventilation setting (conditions 3 and 4). Under the open ventilation setting, the density plots of in-vehicle PM_{2.5} exposures also showed larger variation than in-LRT exposure.

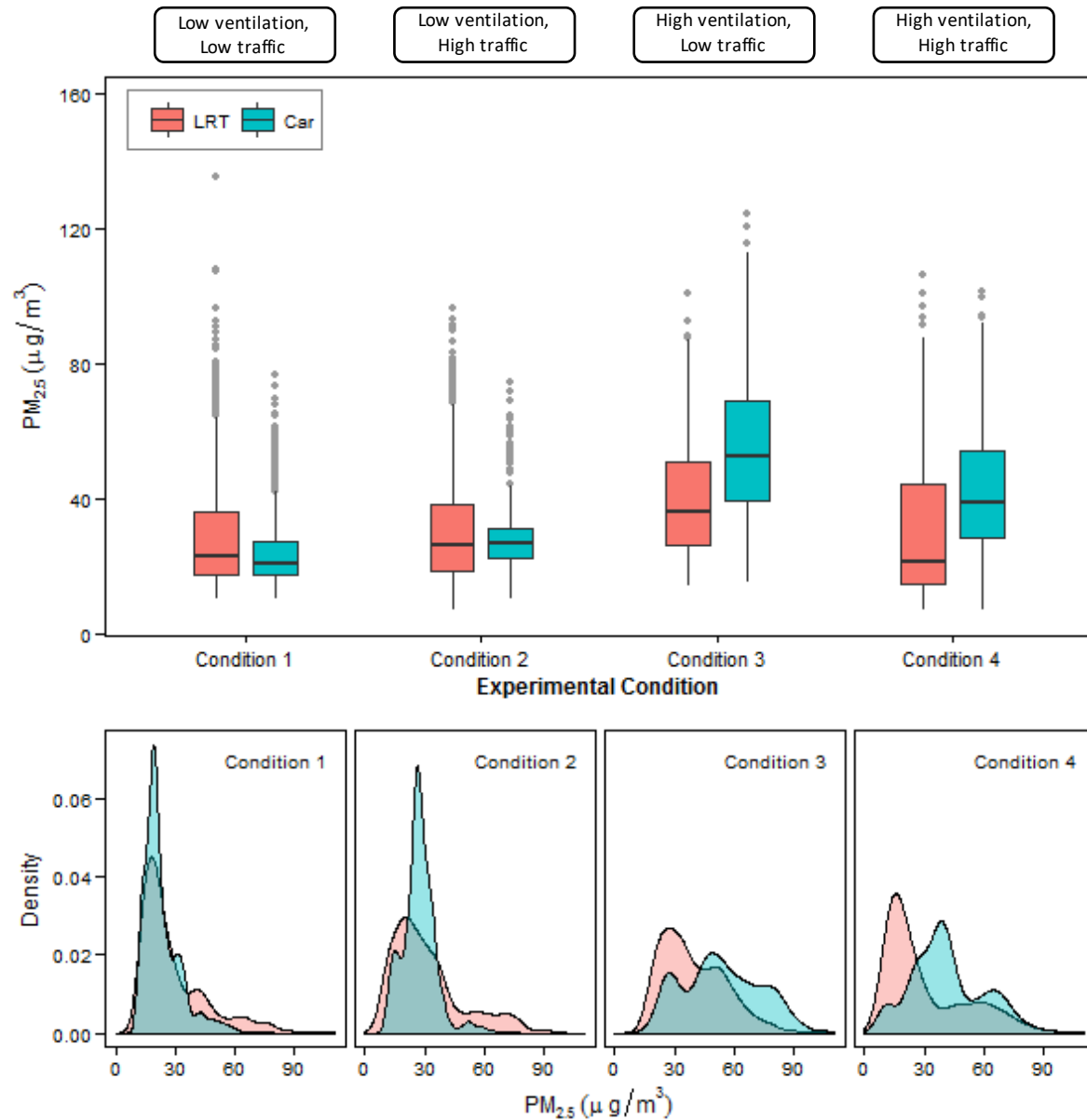


Figure 3. In-LRT and in-vehicle $PM_{2.5}$ concentrations by experimental condition

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic. The probability density was plotted using kernel density function.

BC exposure results showed similar patterns as the $PM_{2.5}$ exposures, but the variance was smaller (Figure 4). Distribution patterns between in-LRT and in-vehicle are similar, but for the conditions 3 and 4, the in-vehicle $PM_{2.5}$ concentration distribution tends to be wider than that of in-LRT concentrations.

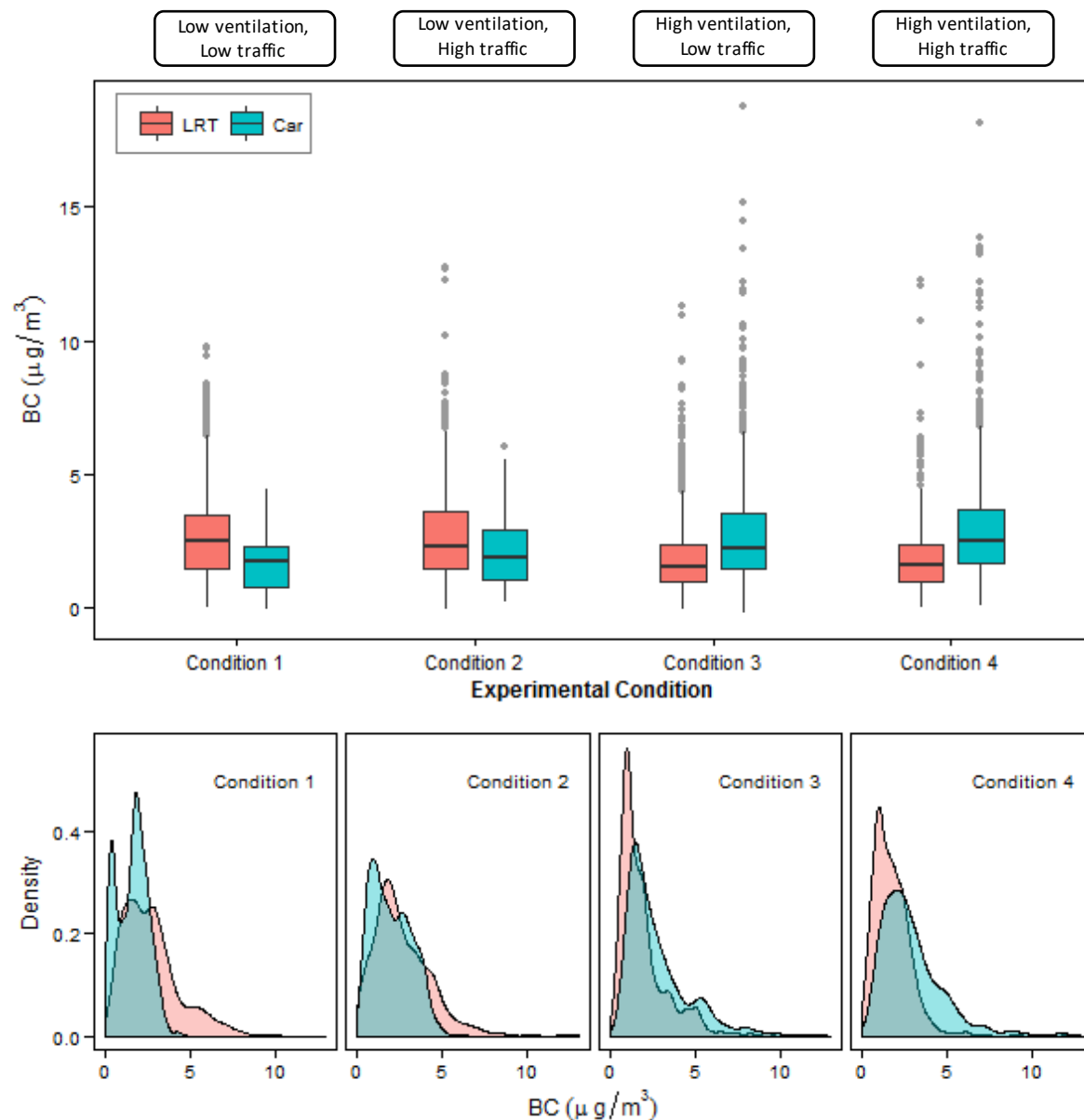


Figure 4. In-LRT and in-vehicle BC concentrations by experimental condition

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic. The probability density was plotted using kernel density function.

UFP number concentrations also follow the similar pattern as the previous two pollutants – small variance under the conditions 1 and 2, and high variance under the conditions 3 and 4 (Figure 5). Especially, there is a stark difference in the results for the condition 1 and condition 4. Under the condition 1 which represents a closed-window environment on highways, UFP number concentrations for in-LRT microenvironment have higher mean than for in-vehicle

microenvironment, but the variance looks much the same for both microenvironments. However, under the condition 4, an open-window environment on highways, in-vehicle concentrations show a substantially higher mean and variance than in-LRT concentrations. This suggests that UFP is more sensitive to changes in the microenvironment than other pollutants, and the experimental conditions with varying ventilation setting and travel route choices sufficiently captured the effects of microenvironmental changes on personal exposure.

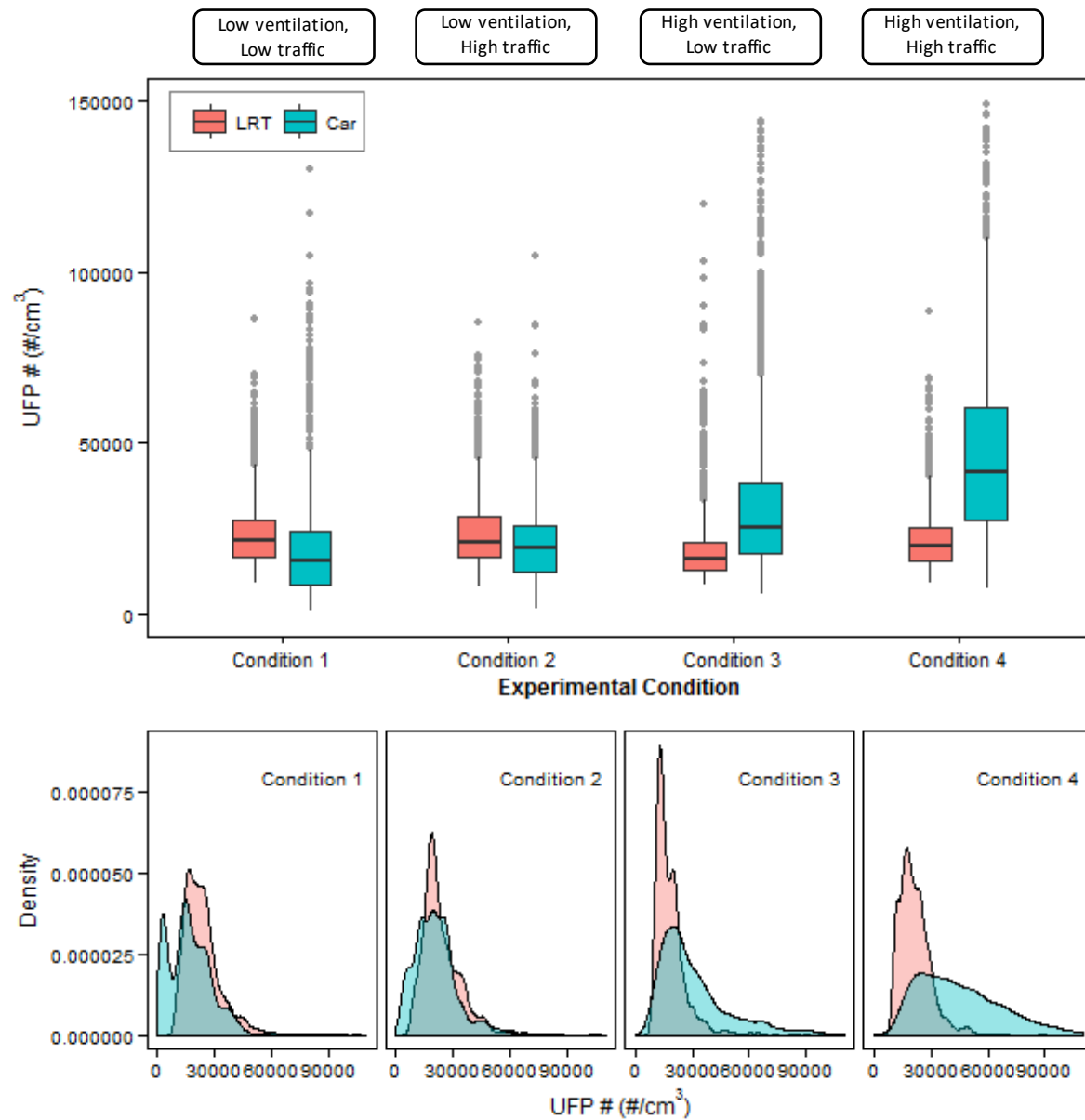


Figure 5. In-LRT and in-vehicle ultrafine concentrations by experimental condition

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic. The probability density was plotted using kernel density function.

337

338 Figure 6 shows the boxplots and the probability density plots for the CO₂ measurements.

339 Compared to the relatively consistent patterns of the in-LRT concentrations, in-vehicle

340 concentrations show wide variations in terms of sample mean and variance. Under the condition

341 1 which represents a closed microenvironment on highways, the mean CO₂ concentrations for

342 the in-vehicle environment is substantially higher than that for the in-LRT environment, and are

343 widely distributed from 0 to 4,000 ppb. Contrasting this result with the condition 4 which

344 represents an open-window microenvironment, the mean values for the in-vehicle environment

345 are much lower than that for the in-LRT environment with much smaller variance.

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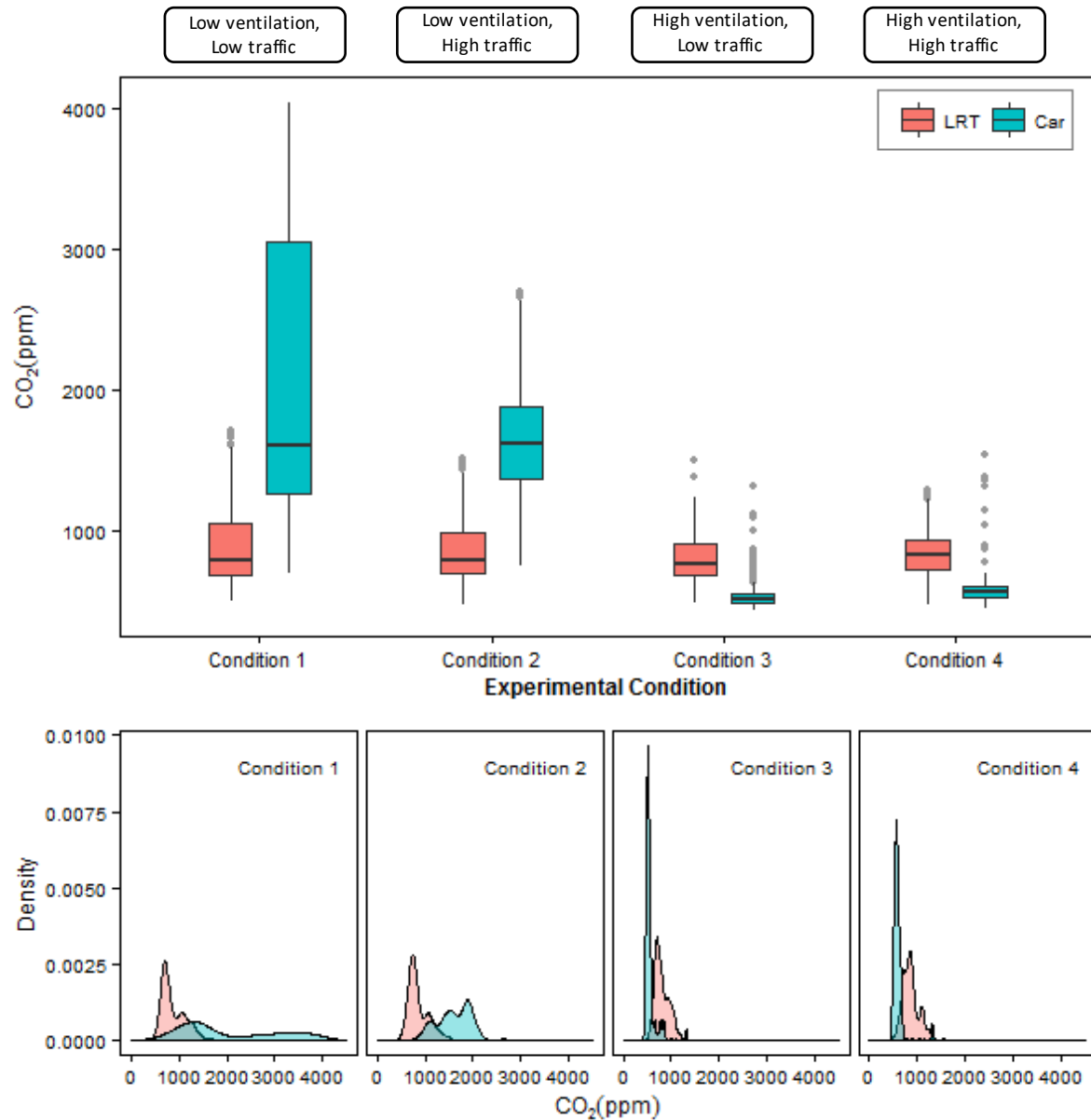


Figure 6. In-LRT and in-vehicle CO₂ concentrations by experimental condition

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic. The probability density was plotted using kernel density function.

3.2. ANOVA results

A one-way between subjects ANOVA was performed to test the four hypotheses regarding the exposure differential between LRT and automobile (Figure 7). The results generally confirm the hypotheses. There was a significant effect of ventilation on the mean difference at the 1% significance level for all the pollutant types (PM_{2.5}: $F_{(3, 3137)}=312.8, p < 0.001$; BC: $F_{(3, 3086)}=327.9, p < 0.001$; UFP#: $F_{(3, 9294)}=973.2, p < 0.001$; CO₂: $F_{(3, 981)}=393.6, p < 0.001$). These

results suggest that ventilation and traffic environment settings have significant effects on modal difference in personal exposure. Specifically, the results suggest that under the open ventilation scenario, switching from car to LRT will lead to a significant reduction in exposure levels, indicated by the negative signs of the mean difference in personal exposure in the experimental conditions 3 and 4. For $PM_{2.5}$, the experimental condition 4 does not appear to significantly differ from the condition 3. However, for BC and UFP number concentrations, the effects of mode switch is more pronounced in condition 4 than in condition 3 (Condition 3: $M = -0.75, p < 0.001$; Condition 4: $M = -0.75, p < 0.001$), suggesting that there is a combined effect of high traffic microenvironment and open ventilation condition. Interestingly, mode switch from car to LRT results in positive mean Δ in the experimental conditions 1 and 2 across all pollutants, except CO_2 . This suggests that, under the close ventilation scenario, switching from car to LRT will result in a higher personal exposure. Unlike the results from the conditions 3 and 4, there is little difference in the effects of traffic on mean Δ when operating in a closed ventilation environment. This result indicates that vehicle cabin and ventilation system provide some form of protection from outside pollutants.

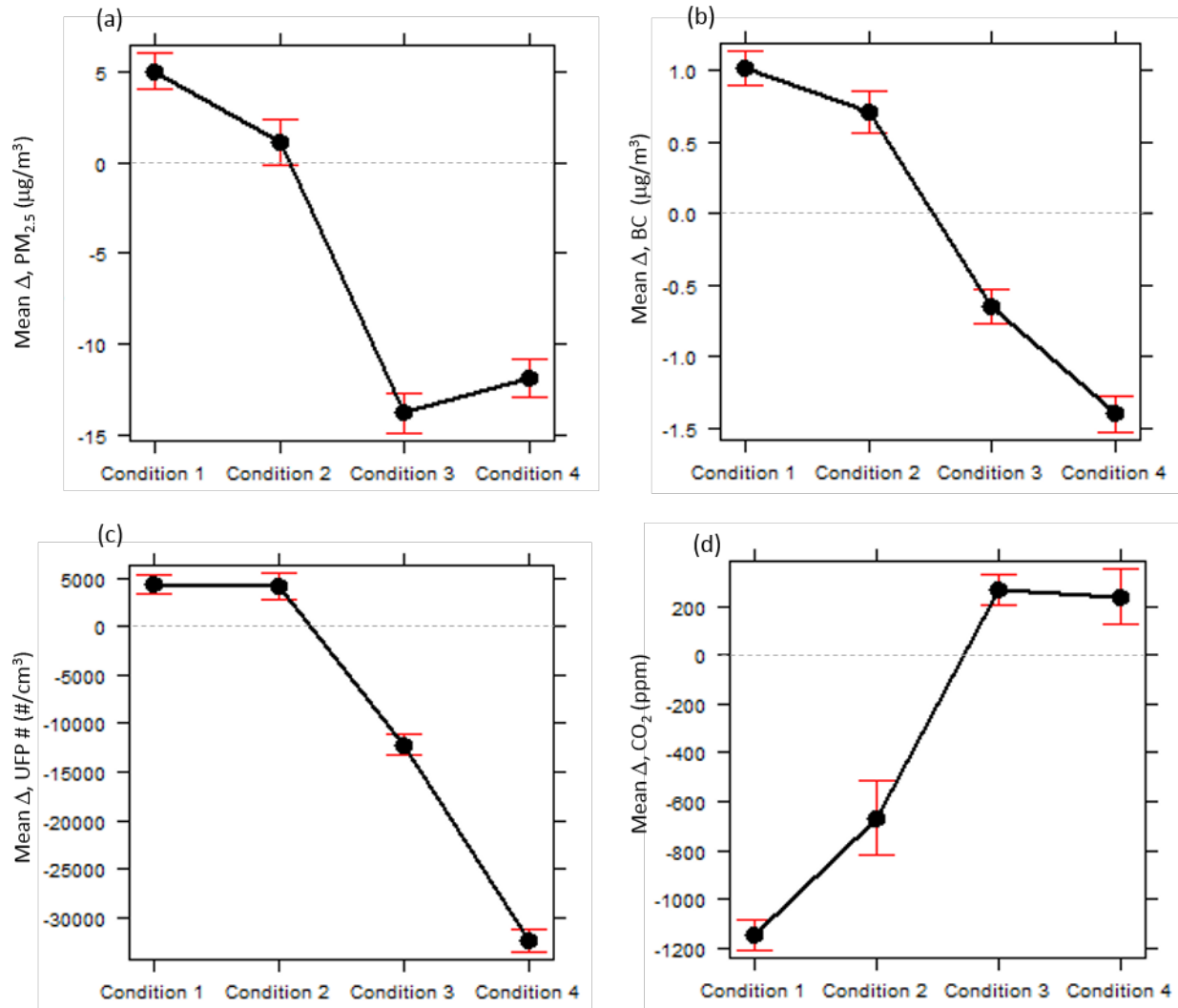


Figure 7. ANOVA results comparing different travel conditions

Note: Condition 1: closed ventilation, low traffic; Condition 2: closed ventilation, high traffic; Condition 3: open ventilation, low traffic; Condition 4: open ventilation, high traffic.

Results of CO₂ are the opposite from the results for PM_{2.5}, BC, and UFP. The mode switch from car to LRT leads to a decrease in exposure when operating in a closed ventilation condition (Conditions 1 and 2) but an increase in exposure when operating in an open ventilation condition (Conditions 3 and 4). This result makes sense because closed ventilation condition inside a vehicle creates an environment where CO₂ gets trapped inside a car. A cabin environment inside LRT is generally more ventilated than a tightly sealed private vehicle, therefore, commuters driving a tightly sealed vehicle would experience a decrease in mean CO₂ levels when switching mode to LRT. Because CO₂ is substantially less toxic than the other three pollutants, the increase in CO₂ in a closed ventilation condition is less of a concern for most people, although long-term

exposure to CO₂ may have a potential adverse effect and raise a concern for some sensitive population.

3.3. Robustness check

The robustness of the results was checked against other vehicle-specific factors. Previous studies suggest that in-vehicle I/O ratios significantly differ between RC (air recirculate) and OA (outside air) setting, and developed predictive functions to estimate in-vehicle I/O ratios for various travel conditions (Fruin et al., 2011; Hudda et al., 2012; Hudda and Fruin, 2013; Ott et al., 2008). In a separate analysis, the I/O ratios computed from the predictive functions (adapted from Hudda et al (2012)) were evaluated against the I/O ratios computed from our own sample, and the predictive functions provided reliable estimates of I/O ratios (Table S5). Using the predictive functions, I/O ratios were calculated for different fan settings under RC and OA condition while holding other parameters at their median values (speed 40 mph and vehicle age 7). Likewise, the I/O ratios for different vehicle speed and vehicle age were calculated while holding other parameters at the mean (Table S6). The calculated I/O ratios were multiplied by the sample measurement obtained from the experimental conditions 3 and 4. It was assumed that the sample measurement from the experimental conditions 3 and 4 is representative of the on-road concentrations for both local streets and highways.

Because the pollutant samples followed a log-normal distribution, a log-normal distribution was used to estimate an empirical distribution function from bootstrap sampling of 10,000 iterations under RC (air recirculate) and OA (outside air) condition. A cumulative distribution function with log-scale was plotted to compare the distributional patterns of in-vehicle against in-LRT exposure for three vehicle-specific factors, including fan strength, vehicle speed, and vehicle age. Bootstrap mean, standard error, and 95% confidence interval were also calculated to provide a statistical property of the empirical distribution.

Effect of fan strength

Three fan settings, low (20%), medium (50%), and high (70%), were chosen to test the effect of fan strength on in-cabin concentrations. Using the calculated estimates of in-vehicle and in-LRT UFP concentrations, a cumulative distribution function was plotted with log-scale for in-vehicle

concentrations under each of the parameter settings. Representative probability distributions of UFP concentrations are shown in Figure 8. The predicted in-cabin concentrations shows that under RC condition, in-LRT concentrations were expected to be two or three-fold higher in exposure than in-vehicle concentrations. Under OA condition, however, in-vehicle concentrations were expected to be 1.5 to 2 times higher than that of in-LRT concentrations. In both conditions, the increase in fan strength from 20% to 70% increased UFP concentrations by 28%. The differences in RC and OA were larger than the uncertainty associated with the fan strength.

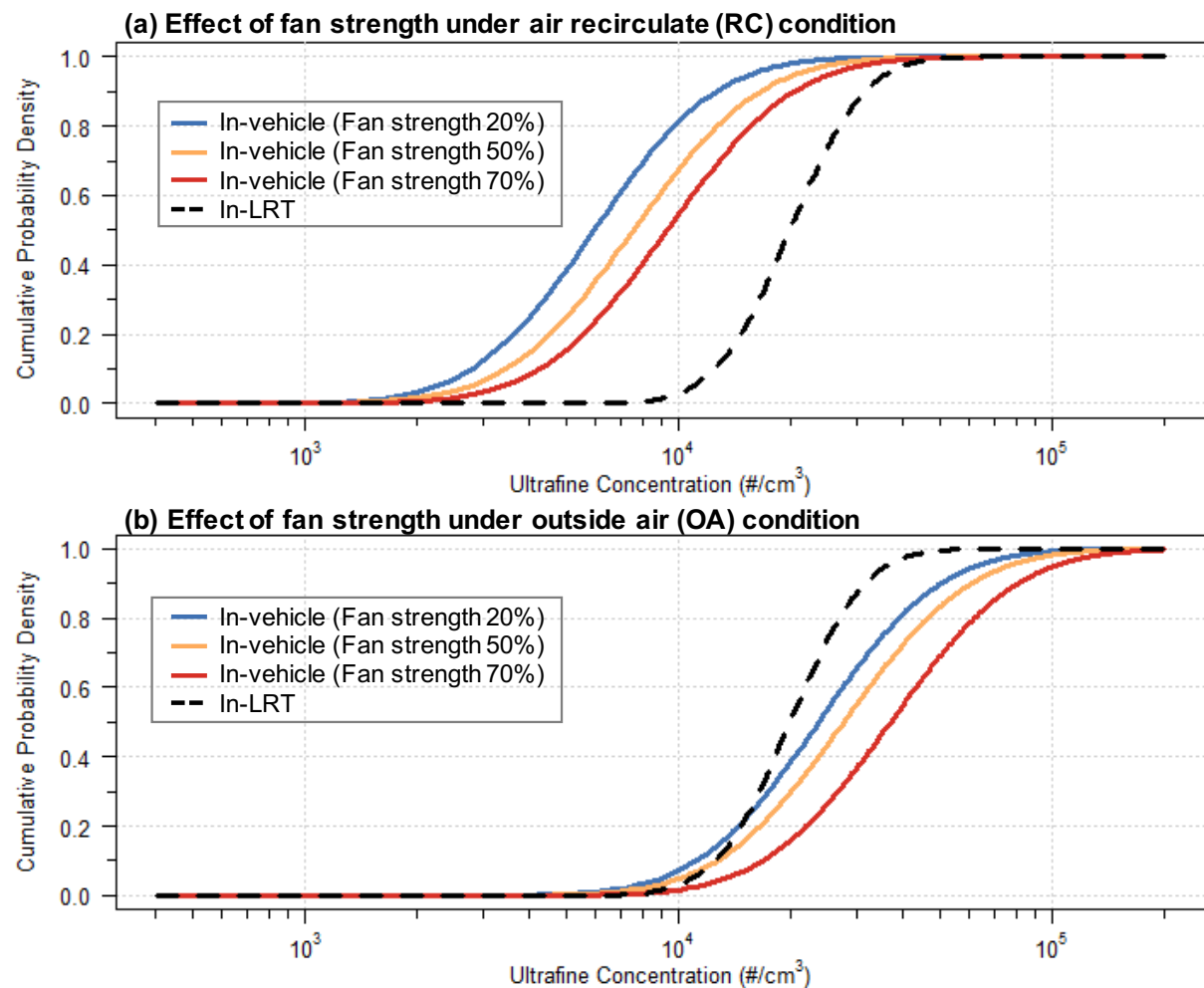


Figure 8. Effect of fan strength on in-vehicle UFP concentrations compared to in-LRT UFP concentrations

Effect of vehicle speed

As shown in Figure 9, three vehicle speeds, low (20 mph), medium (40 mph), and high (60 mph), were arbitrarily chosen to test the effects of vehicle speed on in-cabin UFP concentrations. Under RC condition, in-LRT UFP concentrations were expected to be two to four-times higher than in-vehicle UFP concentrations. As evident from the probability plot, the effect of vehicle speed on in-vehicle UFP concentrations is more pronounced under the RC condition. The increase in vehicle speed from 20 mph to 60 mph increased the in-vehicle UFP concentrations by 50%. However, in-vehicle concentrations were still lower than in-LRT concentrations across all vehicle speed settings for the RC condition. Comparing this result with the OA condition, only a 1.2 to 1.7-fold increase would be expected for in-vehicle concentrations compared to in-LRT concentrations. This means that a driving speed would have little impact on the difference between in-LRT and in-vehicle concentrations if a person typically drives under the OA condition.

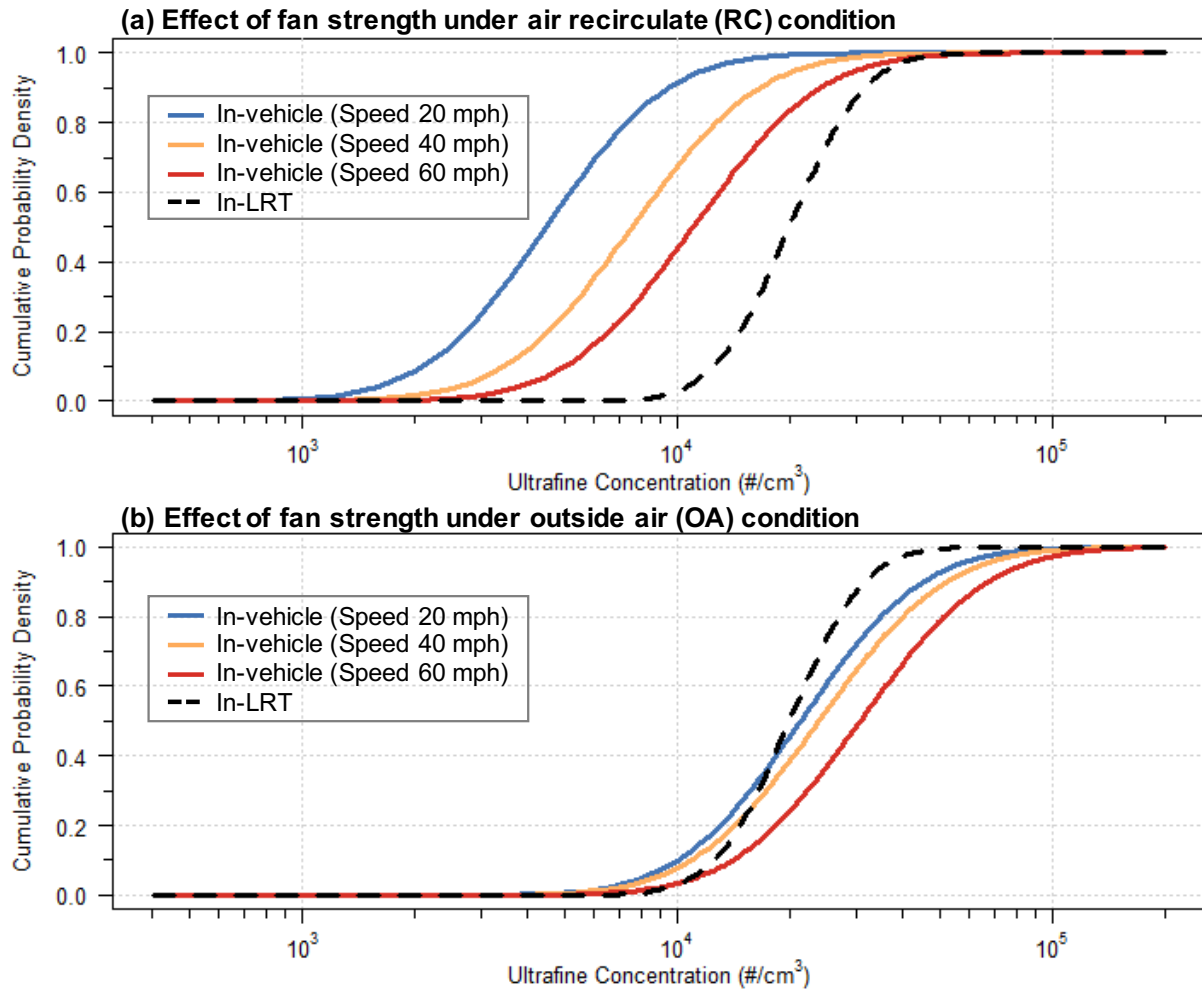


Figure 9. Effect of vehicle speed on in-vehicle UFP concentrations compared to in-LRT UFP concentrations

Effect of vehicle age

To examine the effect of vehicle age on UFP concentrations, three parameters, low (2 years), medium (7 years), and high (11 years), were arbitrary chosen. As can be seen from Figure 10, the effect of age is much more pronounced under the RC condition than the OA condition. Under the RC condition, the increase in vehicle age from 2 to 11 increases in-vehicle UFP concentrations by 46%, whereas the changes in vehicle age under the OA condition have little or no impact on in-vehicle UFP concentrations. Under RC condition, a two to three-fold increase would be expected for in-vehicle UFP exposure compared to in-LRT exposure. Under the OA condition, in-vehicle UFP concentrations are expected to be 1.5 times higher than in-LRT UFP concentrations across the three vehicle ages.

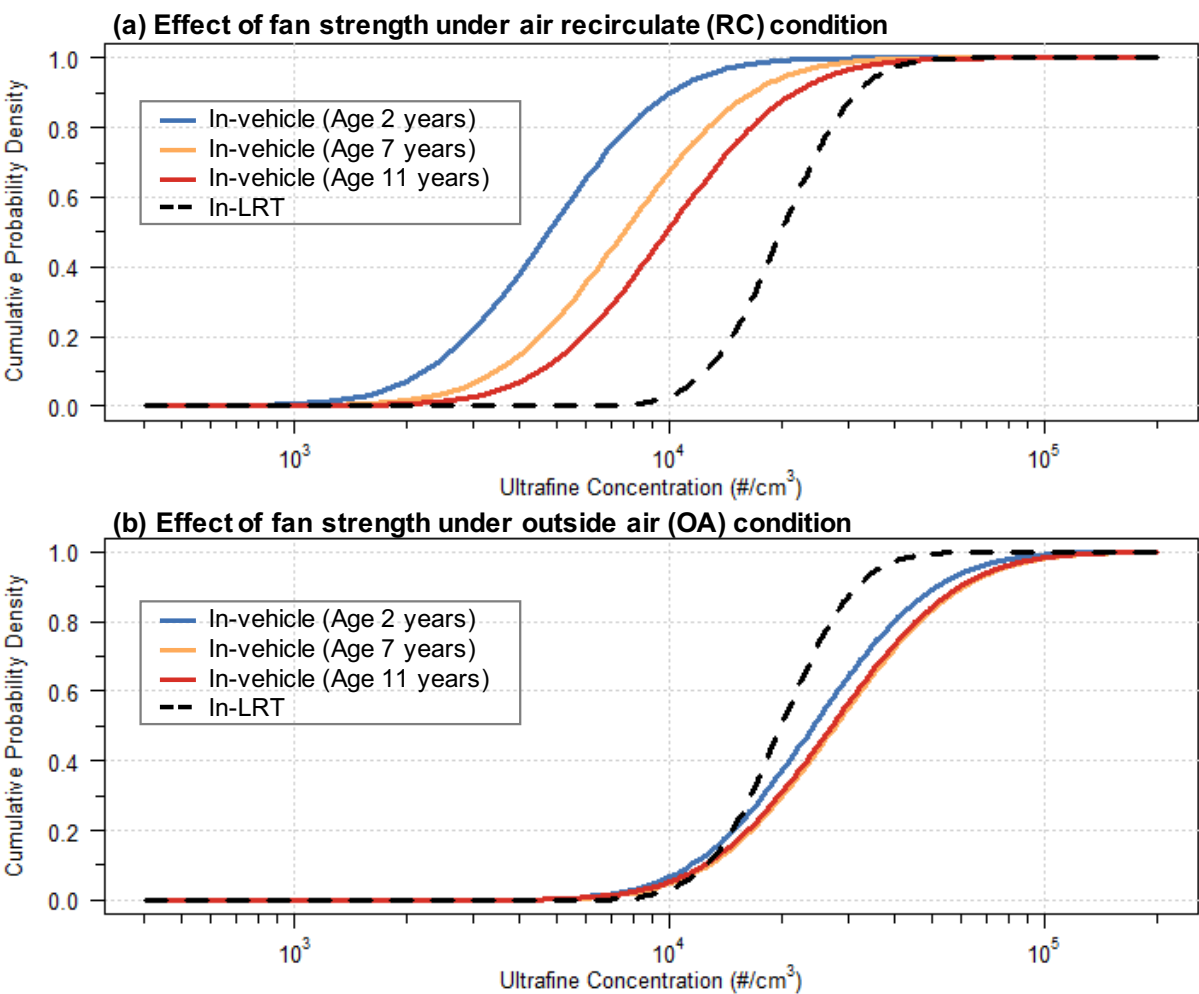


Figure 10. Effect of vehicle age on in-vehicle UFP concentrations compared to in-LRT UFP concentrations

4. DISCUSSION

The controlled experiment provided evidence that both internal and external microenvironments matter when quantifying the effect of mode switch on personal air pollution exposure. The internal microenvironment is relatively stable for LRT commuting, whereas substantial variations exist when driving a private vehicle. Especially, changing from a closed ventilation to an open ventilation increased in-vehicle exposure by more than two-fold across all pollutant measurements. For example, in-vehicle BC exposure was 21 to 40% lower than in-LRT exposure under the closed-window environment; however, in-vehicle exposure was 43 to 68% higher than in-LRT exposure under the open-window environment (Table 2). This finding is consistent with

previous studies of in-vehicle exposure. Hudda & Fruin (2013) found that I/O ratios for in-vehicle PM_{2.5} and UFP were three times higher for the OA (outside air intake) condition than for the RC (air recirculate) condition. Knibbs and his colleagues (2010) found that median I/O ratios for in-vehicle UFP ranged between 2 and 4 depending on vehicle models based on a tunnel study. Quiros and his colleagues (2013) also found that UFP concentrations were 40%-75% higher when driving with open windows as opposed to driving with closed windows and recirculation on. More recently, Chaney et al (2017) found that in-vehicle PM_{2.5} exposure was nearly double (192%) when driving with windows opened compared to driving with windows closed. Ham and his colleagues (2017) also found that ventilation settings of vehicles can reduce in-vehicle exposure by up to 75%.

Our results suggest that a simple comparison of in-LRT exposure and in-vehicle exposure would fail to capture the variations in personal exposure for typical urban commuters. The observed difference between in-vehicle and in-LRT exposure ranged between 18 and 140%. For example, in-LRT BC exposure was generally lower than in-vehicle BC exposure (2.26 µg/m³ vs. 2.37 µg/m³). However, when taking into account fleet characteristics such as ventilation, in-LRT BC exposure was higher than in-vehicle BC exposure when the vehicle was operating under closed ventilation condition (2.69 µg/m³ vs. 1.61 µg/m³). Except for a few recent studies (Chaney et al., 2017; Ham et al., 2017), most previous studies looking at the modal differences in pollutant exposure rarely control for a ventilation condition or make certain assumptions about ventilation condition. For example, Wang and Gao (2011) did not explicitly control for ventilation conditions when measuring PM_{2.5} and fine particle concentrations for different travel modes, yielding unusually lower PM_{2.5} mass concentrations (400% to 1,400% lower) for automobile compared to all other modes. Briggs and his colleagues (2008), which is frequently cited as the most comprehensive study of commuter exposure, conducted in-vehicle measurement with windows closed while acknowledging that the ventilation status is the most important factor of in-vehicle exposure. Due to substantial variation associated with in-vehicle microenvironments, it is critical to consider the ventilation condition of a vehicle when conducting commuter exposure studies involving automobiles.

Another important factor to consider when quantifying the effect of mode shift would be roadway types. Driving on highways was two to three times more polluted (PM_{2.5} and UFP) than driving on local roads when windows were opened (Figure 7). This is perhaps due to the differences in on-road concentrations between local roads and highways (Fruin et al., 2008; Weijers et al., 2004), but there seems to be a combined effect of roadway type and ventilation condition. For example, the effect of switching mode from car to LRT on BC exposure was two to three time larger when roadway type changed from local roads to highways for either closed-window condition or open-window condition (Figure 7). Although the effect of roadway type seems to be less influential than a ventilation condition, the compounding effect of ventilation status and roadway types is a topic that deserves further investigation.

Lastly, some other factors, including a vehicle fan strength, a vehicle speed, and a vehicle age, seem to have marginal but potentially influential impact on personal exposure. Results of the robustness check demonstrated that the fan strength had similar effects on in-vehicle exposure across different settings (Figure 8), while the differences due to vehicle speed and vehicle age were larger (two to three-fold) under the RC condition than under the OA condition (Figure 9 and Figure 10). Especially, the effect of vehicle age on UFP exposure was almost negligible when driving under the OA condition (Figure 10), suggesting that certain vehicle characteristics are more influenced by internal ventilation condition.

Limitations

This study has a few limitations. First, this study did not measure or incorporate minute ventilation rates, which may vary between car drivers and light rail commuters. Ventilation rates are needed to estimate actual inhaled dose and exposure rates. To estimate the health effects of mode switch, further studies will need to incorporate different minute ventilation rates for car drivers and LRT users. Second, the current study only measured concentrations inside a car and an LRT. Because most rail transit users need to travel to and from transit stations, personal exposure during the additional travel to and from the stations may vary significantly from one person to another. Also, personal exposure during the time outside of a car and an LRT can be highly variable. Omission of this extra exposure may have resulted in under-estimation of commuters' exposure. However, with a sufficient sample size, the variation in additional

exposure may follow a stochastic or a random process, in which case, no specific parameterization may be required. Third, the location of the instrument was fixed inside the car and the LRT. It is possible that certain pollutant, e.g. ultrafine particles, may be more affected than other pollutants by the location of the instrumentation, and this could be a fruitful area for further work. Fourth, this study used a light-duty gasoline-fueled vehicle because it is more representative of typical commuters. The Monte Carlo simulation was used to test the effect of other fleet characteristics. However, it would be fruitful to conduct additional experiments using different vehicle types, such as heavy-duty diesel fleet, especially for understanding the effect of mode shift on BC concentrations. Lastly, the sampling campaign took place during one season, and the results may not be representative of all weather conditions. However, the focus of this study was to capture the exposure difference between car and LRT, and the simultaneous measurements allowed us to control for seasonal or meteorological variations that could have confounded the results.

5. CONCLUSIONS

The results of this study suggest that modal difference in commuter exposure between car and LRT is, in large part, driven by ventilation status and travel microenvironments. Other factors, such as roadway type, vehicle fan strength, vehicle speed, and vehicle age, are likely to influence the modal difference in a more subtle way. The effect of ventilation status on personal exposure was several orders of magnitude greater than the effects due to factors related to fan strength, vehicle speed, and vehicle age. No other observed factors resulted in differences large enough to change the effect of mode shift from car to LRT. Therefore, failure to consider ventilation status could result in an incorrect assessment of commuter exposure to traffic air pollution, potentially leading to misguided policy and research. Further studies will need to examine to what extent incorporation of ventilation status in exposure assessment will affect epidemiological analysis of mid- to long-term health effects of mode shift.

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Abbreviations

LRT: Light rail transit; PM_{2.5}: Fine particulate matter (diameter ≤ 2.5 micrometers); UFP: Ultrafine particulate matter (diameter <0.1 micrometers); BC: Black carbon; CO₂: Carbon dioxide; CF: Correction factor; CPC: Condensation particle counter; GPS: Global positioning system; TRB: Transportation Research Board; HEPA: high efficiency particulate air filter; OA: Outside air intake; RC: Air recirculate; I/O ratios: inside-to-outside ratios; μg : microgram; ATN: light attenuation coefficient; ONA: Optical noise-reduction averaging

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Declarations of interest

None

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