In-Cabin Commuter Exposure to Ultrafine Particles on Los Angeles Freeways

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Worldwide people are exposed to toxic ultrafine particles (UFP, with diameters (dp) less than 100 nm) and nanoparticles (NP, dp < 50 nm) under a variety of circumstances. To date, very limited information is available on human exposure to freshly emitted UFP and NP while traveling on major roads and freeways. We report in-cabin and outdoor measurements of particle number concentration and size distributions while driving three vehicles on Los Angeles freeways. Particle number concentrations and size distributions were measured under different vehicle ventilation settings. When the circulation fan was set to on, with substantial external air intake, outside changes in particle counts caused corresponding in-cabin changes approximately 30–60 s later, indicating an maximal air exchange rate of about 120–60 h^{-1}. Maximum in-cabin protection (~85%) was obtained when both fan and recirculation were on. In-cabin and outdoor particle size distributions in the 7.9–217 nm range were observed to be mostly bimodal, with the primary peak occurring at 10–30 nm and the secondary at 50–70 nm. The vehicle's manufacture-installed particle filter offered an in-cabin protection of about 50% for particles in the 7–40 nm size range and 20–30% for particles in the 40 to ~200 nm size range. For an hour daily commute exposure, the in-vehicle microenvironment contributes approximately 10–50% of people's daily exposure to UFP from traffic.

Introduction

Worldwide toxicological and epidemiological studies have associated higher airborne particulate matter (PM) concentrations with increased morbidity and mortality (*1*, *2*). Recent studies have shown that short- and long-term exposure to extremely high levels of PM may cause acute respiratory system responses such as inflammation, allergy, and asthma (*3*, *4*) and numerous long-term health problems including lung cancer and cardiovascular diseases (*5*, *6*).

People are exposed to atmospheric PM on a continual basis, usually under different circumstances and environments: indoor (at home and work), walking on sidewalks or during sports activities, and during everyday commute. During daily commute, drivers and passengers are exposed to short periods of high pollutant concentrations emitted by mobile sources, mainly from on-road vehicles (*7*, *8*). Ultrafine particles (UFPs) are the main components, up to 90% on a number basis, of the PM emitted by on-road vehicles. However, the less numerous but much heavier supermicrometer particles dominate PM mass measurements. Recent literature showed that the concentration of UFPs can be up to 25 times greater adjacent to a busy Los Angeles (LA) freeway than upwind background (*9*, *10*). UFP and nanoparticles (NP) have shown high toxicity in lab animals, and when inhaled, they may enter the circulatory system and deposit on the brain (*11*, *12*). Furthermore, UFPs, as a result of their small size and large surface area, are capable of crossing cellular walls and localize in the mitochondria (*13*).

As a general trend, the number of vehicles in the LA roads and freeways has continuously increased over the years, resulting in congested freeways, larger number of emitters, and much longer commuting times. Approximately 50% of the population spends more than 30 min to travel between home and work one-way each day (*14*). Taking all these factors into consideration, commuter exposure to high concentrations of toxic UFP and NP has become an important issue in risk assessment studies. Recently, a small number of studies have focused on evaluating the on-road particle concentrations (*8*). These studies showed that pollutant concentrations varied widely by location and/or roadway and appeared to be strongly affected by vehicular traffic sources. The presence of heavy-duty diesel (HDD) trucks on a road resulted in a significant increase in particle number concentration. These results indicated that in general drivers and passengers commuting on major roads and freeways are exposed to higher particle concentrations than in other microenvironments. Commuter exposure, or in other words, protection against outdoor pollutants, depends on several parameters such as traffic mix and density, type and age of the vehicle, efficiency of particle filter, and the vehicle's operating ventilation settings.

In this paper we report simultaneous in-cabin and outdoor measurements of particle number concentration and size distributions while driving on busy LA freeways. Three different vehicles were used in the study and the effect of traffic mix, presence of HDD on the road, and in-cabin ventilation settings were evaluated. Overall car protection and commuter exposure were estimated based on in-cabin and outdoor ratios.

Methods

Instruments. Outdoor particles were sampled through a 3 mm (i.d.) isokinetic probe mounted on the car window to ensure a representative UFP sample entered the inlet. Anisokinetic sampling will introduce error but only for large particles where their inertia will make them continue in a straight line as the gas curves into the inlet. UFPs with negligible inertia have little sampling error because they follow the gas streamlines perfectly. For 300 nm particles (the largest particle size studied), with a fixed sampling flow rate of 1.0 L/min, for a sampling probe diameter of 3 mm, sampling errors were calculated to range from 8% to 0% at car speeds of 60 to 5 mph (*15*). A similar probe was used for in-cabin air sampling to compensate for any diffusion loss in the sampling lines. Total particle number concentrations

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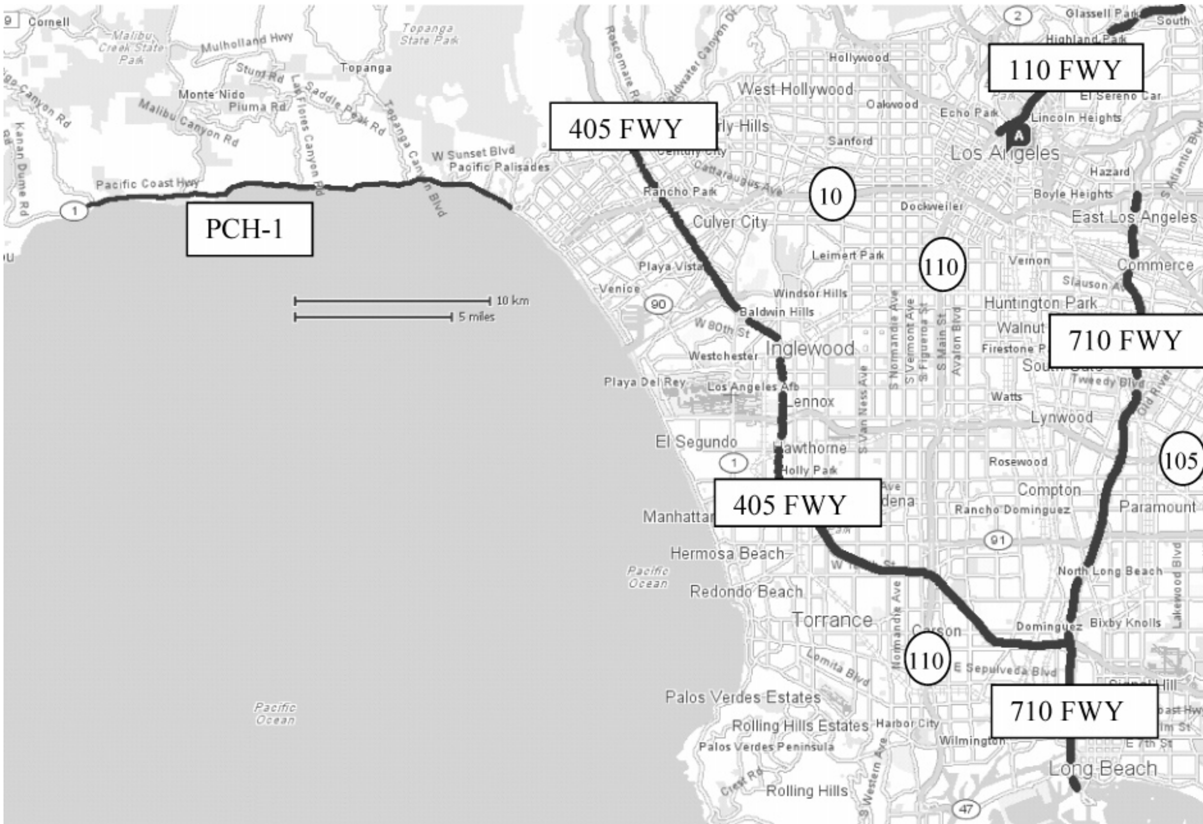


FIGURE 1. Major freeways in which the study was conducted.

were measured using two TSI model 3785 water-based condensation particle counters (WCPC). CPC data were collected in 1-s intervals to provide high temporal resolution results. Particle size distributions, in the 7.9−217 nm diameter range, were measured using two TSI model 3080 scanning mobility particle sizers (SMPS 3936L85, TSI Inc., St. Paul, MN). The sampling flow rate in this experiment was 1.0 L/min to permit measuring particles as small as 7.9 nm. One-minute scans were used for SMPS data collection. SMPS and CPC output were exported to the Aerosol Instrument Manager software (version 5.1, TSI Inc., St. Paul, MN).

Simultaneous measurements of carbon dioxide (CO_2) and carbon monoxide (CO) concentrations and temperature inside the vehicle were carried out at 1-min intervals on a continuous basis by a Q-Trak IAQ monitor (Model 8550, TSI Inc., St. Paul, MN). Q-Trak data were exported to the TrakPro software (version 3.33, TSI Inc., St. Paul, MN). All data reduction and analysis were done in the Statistical Analysis System (SAS version 8.01).

Procedure. Three vehicles, all equipped with a standard manufacture-installed particulate filter with activated carbon, were tested during this study: a Volkswagen Jetta 1.8T (model year 2000), an Audi A4 1.8T (model year 2004), and a PT Cruiser (model year 2005). Windows were closed for all the runs. Ventilation settings tested were as follows: (i) circulation fan off and recirculation (RC) off; (ii) fan on and RC off; and (iii) fan on and RC on. The supply air to the in-cabin environment was from outside under conditions (i) and (ii) and from inside under condition (iii). Fan speed was kept from low to medium for most of the tests. Under condition (i), outside air came into the in-cabin environment through leaks in windows and doors. Under condition (ii), outside air came into the in-cabin environment through a manufacture-installed filter. The effect of in-cabin ventilation settings on particle concentration and size distribution was evaluated under these settings. Each vehicle was tested at least 20 h on freeways. Same ventilation parameters were usually maintained constant for 20 min before switching to different settings. The effect of air conditioning (AC) was also tested but no distinct effect was observed. The results presented below reflect settings with AC on except when the fan was set to off.

This study was conducted in April 2004 and April and July 2005. During this period different routes were driven: I-405 freeway (mainly light-duty vehicles, LDV) (*10*), I-710 freeway (25% of the fleet is HDD) (*9*), and the 110 freeway (only allows LDV from downtown LA to Pasadena) (*16*) (Figure 1). The Pacific Coast Highway 1 (PCH-1), a route following California's coast, was selected as a reference freeway with low traffic and located upwind of the LA air basin. Measurements usually took place between 10 am and 4 pm when on-shore sea breeze was dominant (*9*, *10*). This period was selected to avoid rush hour, although traffic on LA freeways was always busy. The test vehicles were in the traffic stream with an average speed of 50−60 mph for all freeways. The current study focused on providing representative data for typical commuters on LA freeways. No chasing experiment was performed. Meteorological conditions were very similar during all sampling days, with sunny days and no rain. The average (±RSD) temperature and relative humidity were respectively 23.0 ± 3.56 °C and 45.0 ± 11.7%. In-cabin temperature and relative humidity were quite constant throughout this study. Traffic counts, freeway commute time, and measured in-cabin and outdoor average particle concentrations are summarized in Table 1.

Results and Discussion

Particle Number Concentrations. When the fan was on, a large amount of in-cabin air came from external freeway air. Under this condition, in-cabin particle number concentrations followed the outdoor concentrations with a 30−60 s delay, which corresponds to an air exchange rate (AER) of 120−60 h^{-1} (Figure 2). AER would be much less when either

TABLE 1. Traffic Conditions, Traffic Mix, Time of Commute for Each Freeway, and In-Cabin and Outdoor Average ± RSD Particle Concentration ($\times 10^3$/cm^3)[a]

freeway	vehicles/min	traffic mix	time on freeway (min)	outdoor (10^3/cm^3)	VW Jetta 2000 (10^3/cm^3)	Audi 2004 (10^3/cm^3)	PT Cruiser 2005 (10^3/cm^3)
PCH-1	30[b]	<2% diesel[b]	445	22 ± 24	18 ± 3.9	9.0 ± 2.2	9.1 ± 3.3
110	95[c]	gasoline only	60	94 ± 142	25 ± 6.6	20 ± 4.2	22 ± 4.8
405	231± 30[d]	5% diesel[d]	153	239 ± 7.3	200 ± 48	90 ± 21	85 ± 19
710	203 ± 12[e]	~25% diesel[e]	95	256 ± 119	290 ± 67	n/a[f]	150 ± 34

[a] Ventilation settings tested were as follows: (i) circulation fan off and recirculation (RC) off; (ii) fan on and RC off; and (iii) fan on and RC on. [b] Present study. [c] Kuhn et al. (*16*). [d] Zhu et al. (*10*). [e] Zhu et al. (*9*). [f] The Audi 4 was not tested on the 710 freeway.

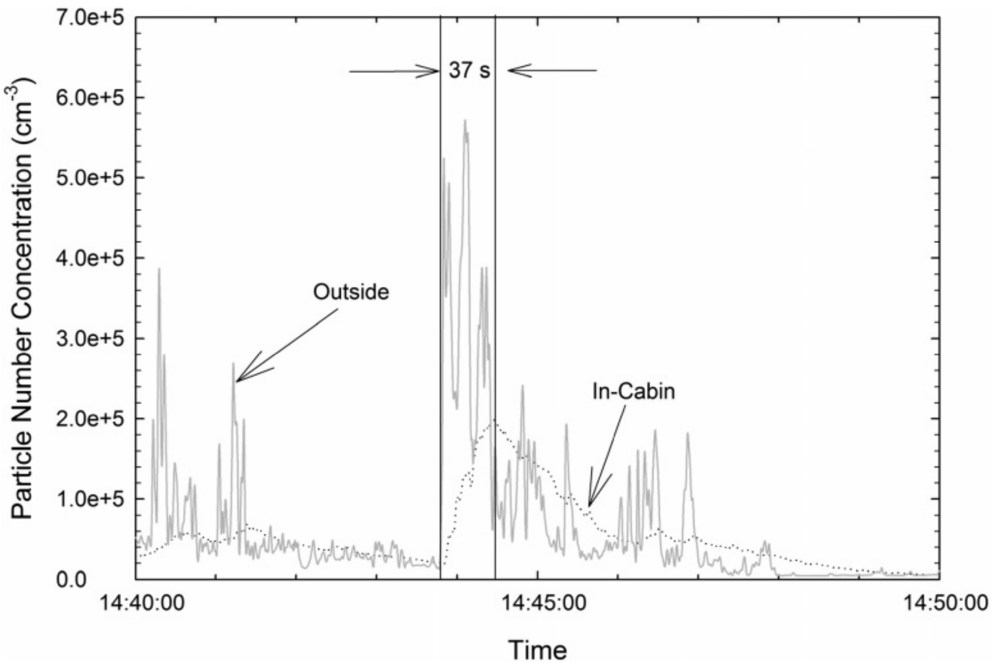


FIGURE 2. In-cabin and outside particle number concentrations observed on 04/21/05 while driving the VW Jetta on the PCH1 highway (fan on, AC on, and RC off).

fan was off or recirculation (RC) was on. Both brought little external air into the in-cabin environment. Outside the vehicle, particle number concentration varied significantly while driving on freeways. The rapid changes observed in the outside particle number concentrations shown in Figure 2 result from changes in the position of the test vehicle in the traffic, the traffic speed, and meteorological conditions, such as wind direction and speed, and temperature. It has been reported that a significant portion of UFPs are comprised of semivolatile organics formed by nucleation and condensation after the exhaust leaves the tailpipe (*17*, *18*). UFP formation is extremely sensitive to the temperature and humidity (*19*) of the surrounding air and how fast the vehicle travels, thus how fast the exhaust is diluted.

The in-cabin particle number concentration did not change as sharply as those on the freeway as shown by the smoother dotted line in Figure 2. This is because in-cabin space served as a chamber damping down the outside variation. However, similar to outside UFP number concentration, in-cabin particle number concentrations also varied considerably with respect to different freeways, thus different traffic volume and vehicle mix. Table 1 summarizes averaged outside and in-cabin particle number concentrations observed from three vehicles driving on different freeways. Data were time-averaged over all applied ventilation settings. In-cabin UFP number concentrations were the highest on the I-710 freeway which has the highest percentage of diesel vehicles (Table 1). In-cabin particle number concentrations as high as 8×10^5 particles/cm^3 were observed while driving on the I-710 freeway. These observations are consistent with previously reported results, in which a linear relationship between diesel traffic and on freeway UFP number concentration was found (*8*).

Figure 3 depicts average in-cabin to outdoor particle number concentration ratios with respect to different ventilation settings for the tested vehicles, together with the overall commuter protection (right-hand *y*-axis). The overall protection varied between 20% for the VW Jetta with the ventilation setting of fan off, and no recirculation, and 90% for the PT Cruiser (newest vehicle tested) when the fan and the recirculation were both on. These results indicate that a car's age plays an important role in commuter protection; the older the car was, the higher the particle penetration. A higher particle penetration in older cars may be due to higher leakage when the ventilation is off as the sealing efficiency of doors and windows decrease over time. Maximum protection, 80–90%, was observed when both the recirculation system and the fan were on. Under this condition, there is reduced incoming air from outdoors. Moreover, particle deposition on in-cabin surfaces may also help to reduce the particle number concentration.

Particle Size Distribution Measurements. Time-resolved UFP size distributions (7.9–217 nm size range) measured outside and inside of the PT Cruiser on the I-710 freeway are shown as contour plots in Figure 4. The *x*-axis presents the time at which data were collected; the *y*-axis is the particle

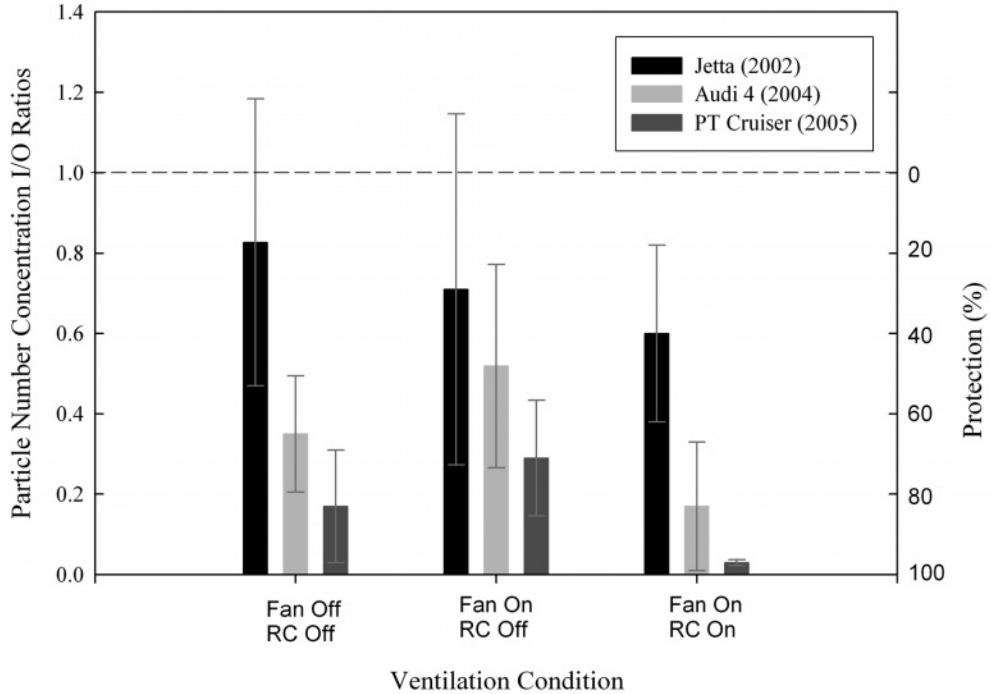


FIGURE 3. In-cabin and outdoor average particle concentration ratios for different cars and different ventilation settings. I/O ratios were obtained from 1-min averaged in-cabin and outdoor particle concentrations. At least 60 1-min I/O ratios were used for each bar. Fan: circulation fan; RC: recirculation. Right-side *y*-axis presents the percent protection vehicles provided.

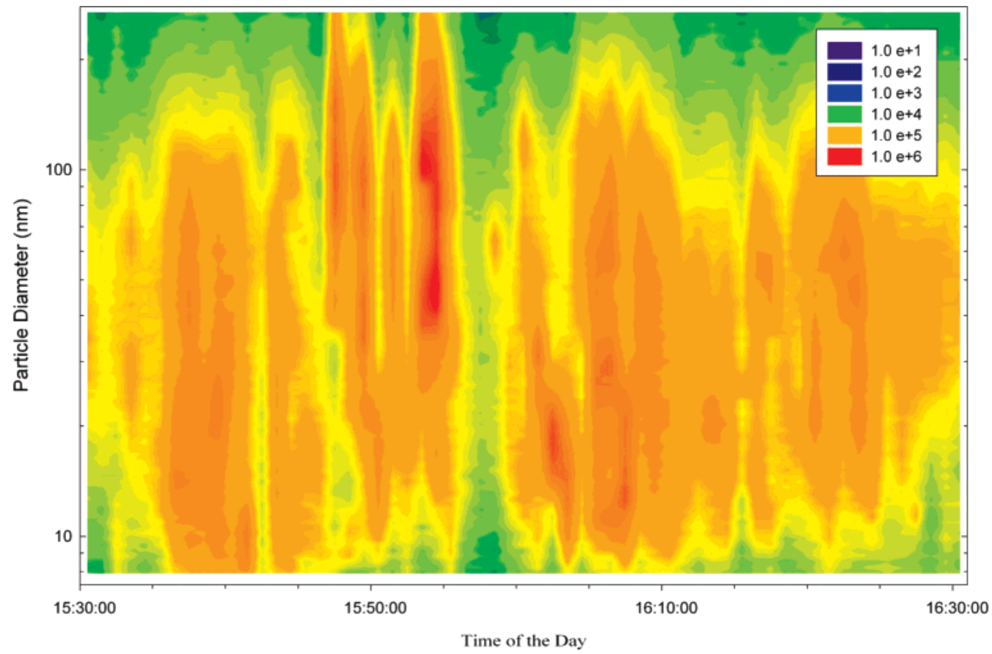
size in log scale and the color intensity indicates normalized particle number concentration (dN/d Log Dp) for a given size at a given time. The same color scale was used for UFP concentrations outside and in-cabin. Data were collected when both the fan and recirculation (RC) were set to on which, as shown in Figure 3, provided maximal protection to the in-cabin environment. The vehicle protection can also be observed by the much bluer color in Figure 4b. In general, large variations were observed for outside UFP concentrations. In-cabin UFPs tracked their outdoor counterpart with respect to both size and intensity. Bimodal distributions were observed for both outdoor and in-cabin size distribution with mode diameters around 10−20 and 50−70 nm.

Average outdoor and in-cabin particle size distributions on different freeways are shown in Figure 5. Data presented in this figure were collected with the PT Cruiser. Raw data (dots) were fitted to bimodal log-normal distributions (lines) using DistFit software (Chimera Technologies, Inc., Forest Lake, MN). The count medium diameters (μ_g) and geometric standard deviations (σ_g) for each mode are given in the figure. Similar to particle number concentration, in-cabin UFP size distributions are much smoother both over time and over particle diameter than those of the outdoors due to the chamber damping effect. The mechanism involved here is analogous to taking "running average" of time-series data where in-cabin particle size distributions were running averages of weighted outdoor particle size distributions modified by I/O ratios. Because this mechanism applies to all particle sizes simultaneously, the in-cabin size distributions became smoother over particle size and over time. A similar effect has been observed in houses located near freeways (*20*). The general form and shape of the in-cabin UFP size measurements are similar to those observed outdoors on the three freeways (Figure 5).

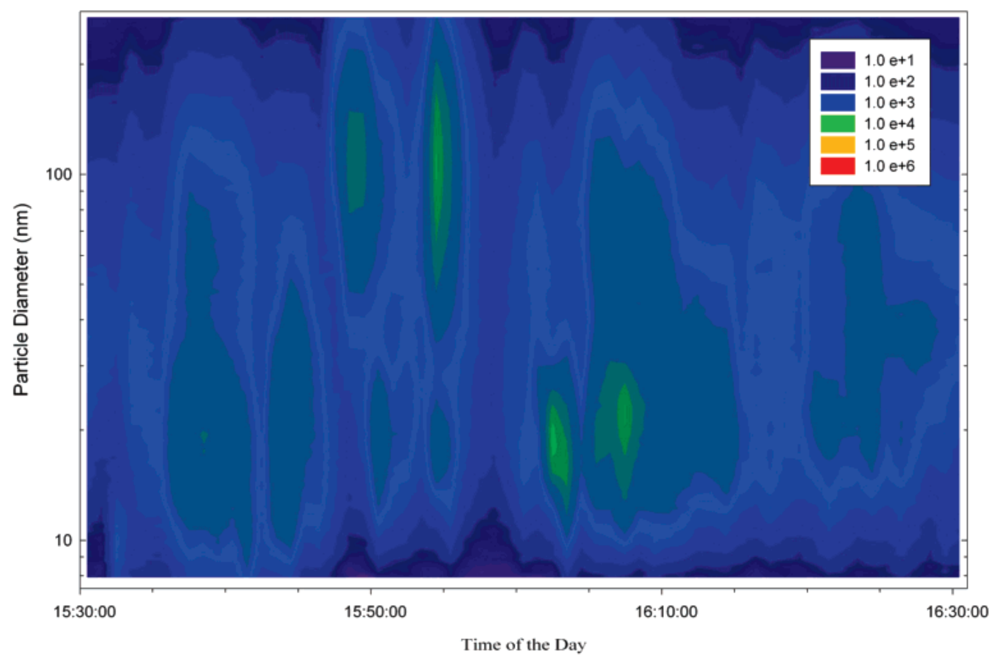
The I-710 freeway, which has more than 25% diesel traffic (*9*), showed a typical bimodal size distribution with modes occurring at 10−20 and 50−70 nm in both outdoor and in-cabin environments (Figures 5a and 5b). Diesel emissions are known to have typical bimodal size distributions with a nuclei mode around 10−30 nm mainly made of sulfate and heavy hydrocarbons. This mode was formed by condensation from super saturation of volatile material after the exhaust leaves the tailpipe and is diluted in the atmosphere (*18*, *21*). This mode is very sensitive to atmospheric conditions, i.e., temperature and relative humidity (*19*). Our measurements were carried out during spring and summer; however, we expect the observed mode concentration to be significantly higher during winter, when temperature conditions are more favorable for nucleation processes. The mode around 50−70 nm was previously reported to consist mainly of solid soot and ash particles formed in the cylinder and was less sensitive to atmospheric conditions (*21*).

The bimodal characteristic of the particle size distribution observed on the I-710 freeway (Figure 5) became less obvious on the I-405 and 110 freeways. The I-405 freeway carries about 5% diesel traffic whereas the 110 freeway is a passenger car only freeway. Previous studies conducted on roadside near freeways found that UFP number concentrations and size distributions were not significantly different between I-405 and I-710 (*9*). However, on-freeway measurements showed a distinct difference between the two freeways. This difference may be due to the fact that near roadway, as compared to on-roadway measurements, reflects a time-integrated effect of all the passing vehicles. However, on freeway measurements are more likely to be affected by the nearby vehicles. With each diesel truck accounting in length for ~3 cars, the percentage of total freeway space dominated by trucks was equivalent to ~14% for the I-405 and ~50% for the I-710 freeway. This means that the test vehicle would have a 14% and 50% chance, respectively, to be in a truck's plume on the I-405 and I-710 freeways. This translated into a much stronger signature of diesel emissions on the I-710 freeway. These findings suggest that commuters driving in freeways with a significant number of HDD will be more exposed to smaller UFPs and as result may be more susceptible to adverse health effects associated with these toxic particles.

Even though significantly different UFP size distributions were observed on different freeways, the characteristics of size-specific in-cabin to outdoor UFP concentration ratios



(a) Outdoor



(b) in-cabin

FIGURE 4. (a) Outdoor and (b) in-cabin time series, size-specified ultrafine particle number concentration contour plots collected with the PT Cruiser on the I-710 freeway under fan on and recirculation on (maximal protection) conditions. Color intensity is normalized particle concentration (d*N*/d Log *Dp*) in log-scale with unit of particle/cm^3.

were very similar (Figure 6a). These results were collected with the same test vehicle, PT Cruiser, under the same ventilation setting (Fan off and RC off) while commuting on different freeways. For all three freeways, the vehicle provides from 48% to 87% protection for particles smaller than 100 nm; for particles larger than 100 nm protection decreases to 33−54% (Figure 6a). This is also similar to the penetration characteristic of freeway UFP into indoor environments (*20*). Although a continuous decrease in commuter protection from 10 to 100 nm was expected, a decrease in the I/O ratio for particles sizes from 20 to 60 nm was observed. This increase in protection may be due to a much higher efficiency of the car, as a whole, to remove particles in this size range. Further studies are needed to understand and characterize the effects that lead to this observation. The I/O ratios were strikingly similar among the three freeways, which implies that the percentage of protection commuters receive from the vehicle does not depend on the outdoor environment. This is not surprising because particle penetration and deposition mechanisms, which determine the I/O ratios, are only a function of particle size and vehicle characteristics.

As shown in Figure 6b, the in-cabin to outdoor size distribution ratio profiles depend on the ventilation settings. The vehicle provided least protection when both fan and RC were set to off. When fan was set to on, it helped to reduce UFPs from getting into the in-cabin environment, especially

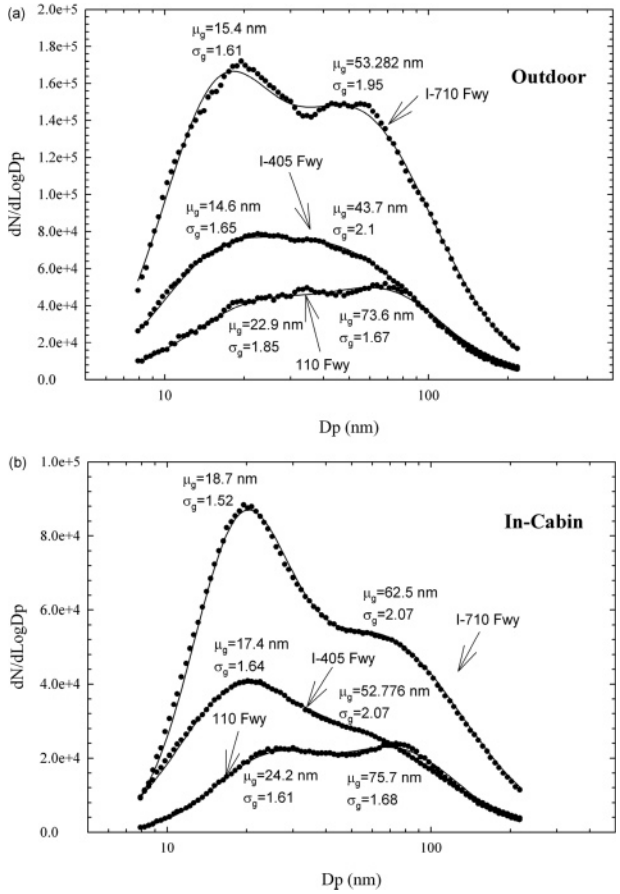


FIGURE 5. Average (a) outdoor and (b) in-cabin ultrafine particle size distributions collected with the PT Cruiser on different freeways.

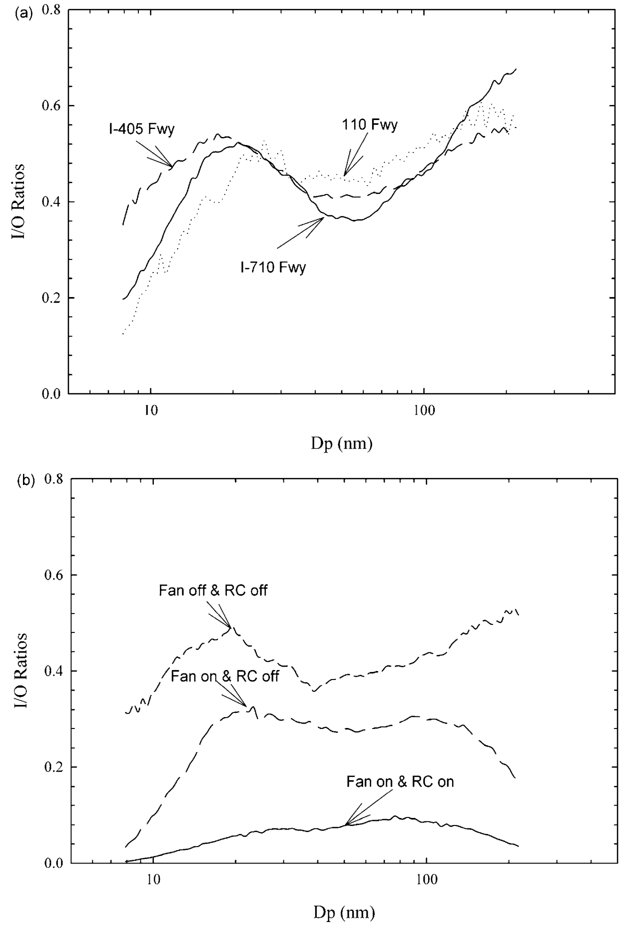


FIGURE 6. Size-specific in-cabin to outdoor ultrafine particle concentration ratios collected with the PT Cruiser (a) on different freeways under fan off and recirculation (RC) off conditions and (b) under different ventilation settings on all three freeways.

for particles larger than 100 nm. This suggests that the manufacture-installed filter is efficient for these larger particles. The major effect of the ventilation settings in the I/O ratio is observed when both the fan and RC were on. A significant drop in the I/O ratios indicates that in-cabin particle number concentration decreases considerably across all size range. It is clear then that particle deposition onto the in-cabin surfaces and particle removal by the filter may constitute the major processes controlling the size distribution and particle number in each measured size range. Results presented in Figures 4−6 refer to the PT Cruiser. Higher in-cabin UFP concentrations for the Audi 4 and even higher concentrations for the Jetta were expected because, as shown in Figure 3, the I/O ratios for total particle number concentrations were greater for these vehicles.

Among the conditions tested, driver and passengers get maximum protection against outdoor particles when commuting in relatively new cars equipped with manufacture-installed particle filtration system when the fan and recirculation are both on. The extent of the protection will depend on the efficiency of the installed filters which calls for further investigation.

Results of this study indicate that daily commuters may be highly exposed to freshly emitted UFPs and that a 1 h commute on busy Los Angeles freeways (with ~100 thousand particles/cm^3) is equivalent to ~10 h of exposure in clean urban background environments away from a freeway (with ~10000 particles/cm^3). On average, Californians spend 6% of their day in vehicles, 7% outdoors, and 87% in various indoor environments (*22*). Assuming an average I/O ratio of 0.6 for UFP penetrating indoor environments (*20*), total daily exposures to UFPs were estimated to be 65000 and 12000 particles/cm^3, respectively, for people who live and work immediately next to a major freeway (~100 thousand particles/cm^3) and who do not (~10000 particles/cm^3). The in-vehicle microenvironment contributed approximately 10% and 50%, respectively, to the above two cases.

Carbon Monoxide and Carbon Dioxide Concentrations. CO concentrations measured during the course of this study were fairly constant and near urban background levels. Average in-cabin CO concentration was 2.5 ppm ranging from 0.1 to 8.1 ppm. Average outside on-freeway CO concentration was 2.4 ppm ranging from 0.1 to 8.0 ppm. No statistically significant difference was observed between in-cabin and outside CO levels. Brief exposure to CO concentration at these levels are of minimal health concern.

The effect of ventilation on particle count, particle decay, and in-cabin carbon dioxide (CO_2) concentrations with or without intake of outdoor air are shown in Figure 7. The fact that in-cabin particle number concentration increases when outdoor air comes into the in-cabin environment (fan on) suggests that the manufacture-installed particle-filter efficiency is not 100% for freshly emitted UFPs.

In-cabin CO_2 concentrations were also monitored continuously while driving on freeways. Monitoring in-cabin CO_2 levels is important for commuter health because, at high concentrations, CO_2 is known to cause headaches, rapid lung ventilation, dizziness, sweating, and increased heart rate (*23*). Occupational Safety and Health Administration (OSHA) has established a 5000 ppm as the Permissible Exposure Limit (PEL) for CO_2 for 8 h. In this study we found that vehicle ventilation settings significantly affect in-cabin levels of CO_2.

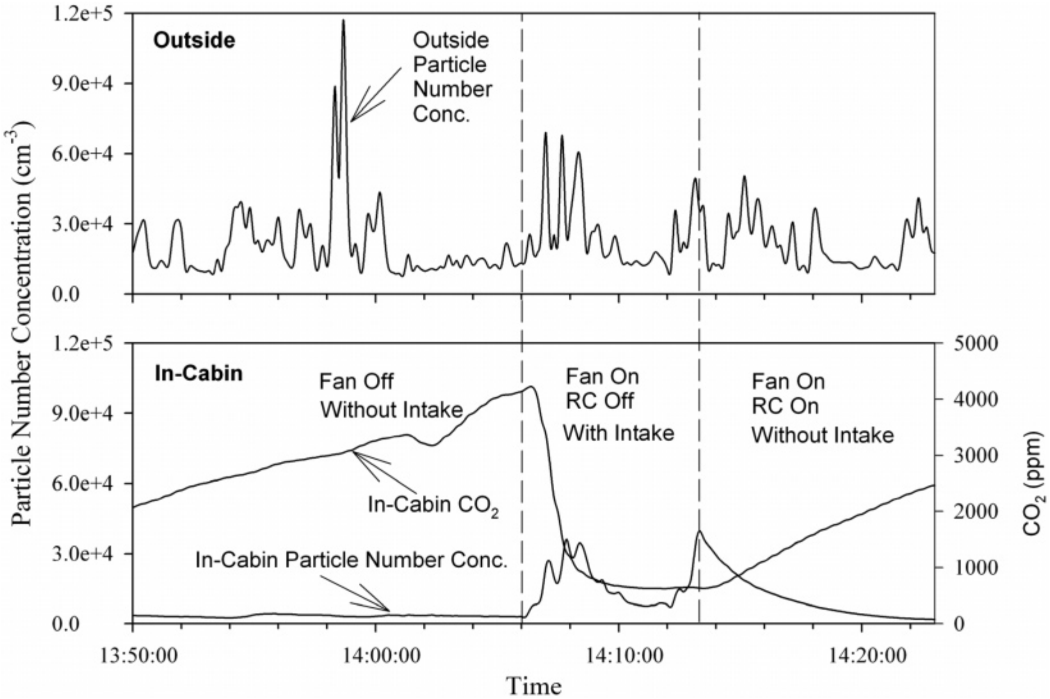


FIGURE 7. Effect of ventilation settings on particle number concentrations and CO_2 measured in the Audi A4 on the PCH-1 with three passengers on board.

In general, with intake of outside air, low levels of CO_2 were observed. When the ventilation settings were changed to recirculation on to give commuters maximum protection against particles, with three persons riding in the vehicle, CO_2 levels rapidly increased reaching up to ~4500 ppm in less than 10 min (Figure 7). In-cabin concentrations of CO_2 may not be considered an issue as long as there is sufficient intake of outside air, but when recirculation is on, the CO_2 concentrations can reach significantly high levels that may affect commuters. During extremely long commutes (e.g., over an hour one way) with more than three passengers in a well-sealed vehicle, it is recommended to either open the window or turn off the recirculation and increase the fan speed approximately once every half an hour to prevent CO_2 concentrations from building up to levels of concern.

People inside the vehicle not only influence CO_2 concentrations but also UFP concentrations. The human respiratory system removes UFPs, thereby reducing their concentrations. This effect may not be important inside well-ventilated vehicles with significant influx of outside air. However, for a well-sealed car with three passengers and no outside air intake (left-most panel in Figure 7), the extremely low in-cabin UFP concentrations were most likely resulted from UFP deposition onto both vehicle interior surfaces and passengers' respiratory systems.

In summary this study has shown that car age and ventilation settings play major roles in the in-cabin commuter exposure to freshly emitted UFP. Commuters are advised to maintain the optimum ventilation settings to get maximum protection against these particles by turning on both the fan and the recirculation.

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Literature Cited

(1) Pope, C. A.; Dockery, D. W. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manage. Assoc.* **2006**, *56*, 709−742.

(2) Dockery, D. W.; Pope, C. A.; Xu, X. P.; Spengler, J. D.; Ware, J. H.; Fay, M. E.; Ferris, B. G.; Speizer, F. E. An Association between Air-Pollution and Mortality in 6 United-States Cities. *New Engl. J. Med.* **1993**, *329*, 1753−1759.

(3) Li, N.; Hao, M. Q.; Phalen, R. F.; Hinds, W. C.; Nel, A. E. Particulate air pollutants and asthma—A paradigm for the role of oxidative stress in PM-induced adverse health effects. *Clin. Immunol.* **2003**, *109*, 250−265.

(4) Sullivan, J.; Sheppard, L.; Schreuder, A.; Ishikawa, N.; Siscovick, D.; Kaufman, J. Relation between short-term fine-particulate matter exposure and onset of myocardial infarction. *Epidemiology* **2005**, *16*, 41−48.

(5) Delfino, R. J.; Sioutas, C.; Malik, S. Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health. *Environ. Health Perspect.* **2005**, *113*, 934−946.

(6) Kunzli, N.; Tager, I. B. Air pollution: from lung to heart. *Swiss Med. Weekly* **2005**, *135*, 697−702.

(7) Marshall, J. D.; Behrentz, E. Vehicle self-pollution intake fraction: Children's exposure to school bus emissions. *Environ. Sci. Technol.* **2005**, *39*, 2559−2563.

(8) Westerdahl, D.; Fruin, S.; Sax, T.; Fine, P. M.; Sioutas, C. Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles. *Atmos. Environ.* **2005**, *39*, 3597−3610.

(9) Zhu, Y. F.; Hinds, W. C.; Kim, S.; Shen, S.; Sioutas, C. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmos. Environ.* **2002**, *36*, 4323−4335.

(10) Zhu, Y. F.; Hinds, W. C.; Kim, S.; Sioutas, C. Concentration and size distribution of ultrafine particles near a major highway. *J. Air Waste Manage. Assoc.* **2002**, *52*, 1032−1042.

(11) Oberdorster, G.; Sharp, Z.; Atudorei, V.; Elder, A.; Gelein, R.; Lunts, A.; Kreyling, W.; Cox, C. Extrapulmonary translocation of ultrafine carbon particles following whole-body inhalation exposure of rats. *J. Toxicol. Environ. Health-Part A* **2002**, *65*, 1531−1543.

(12) Oberdorster, G.; Sharp, Z.; Atudorei, V.; Elder, A.; Gelein, R.; Kreyling, W.; Cox, C. Translocation of inhaled ultrafine particles to the brain. *Inhalation Toxicol.* **2004**, *16*, 437−445.
(13) Li, N.; Sioutas, C.; Cho, A.; Schmitz, D.; Misra, C.; Sempf, J.; Wang, M. Y.; Oberley, T.; Froines, J.; Nel, A. Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage. *Environ. Health Perspect.* **2003**, *111*, 455−460.
(14) U.S. Census Bureau. http://factfinder.census.gov/home/saff/main.html?_lang=en, 2000.
(15) Hinds, W. C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, 2nd Edition*; Wiley: New York, 1999.
(16) Kuhn, T.; Biswas, S.; Fine, P. M.; Geller, M.; Sioutas, C. Physical and chemical characteristics and volatility of PM in the proximity of a light-duty vehicle freeway. *Aerosol Sci. Technol.* **2005**, *39*, 347−357.
(17) Sakurai, H.; Park, K.; McMurry, P. H.; Zarling, D. D.; Kittelson, D. B.; Ziemann, P. J. Size-dependent mixing characteristics of volatile and nonvolatile components in diesel exhaust aerosols. *Environ. Sci. Technol.* **2003**, *37*, 5487−5495.
(18) Kittelson, D. B.; Watts, W. F.; Johnson, J. P. Nanoparticle emissions on Minnesota highways. *Atmos. Environ.* **2004**, *38*, 9−19.
(19) Zhu, Y. F.; Kuhn, T.; Mayo, P.; Hinds, W. C. Comparison of daytime and nighttime concentration profiles and size distributions of ultrafine particles near a major highway. *Environ. Sci. Technol.* **2006**, *40*, 2531−2536.
(20) Zhu, Y. F.; Hinds, W. C.; Krudysz, M.; Kuhn, T.; Froines, J.; Sioutas, C. Penetration of freeway ultrafine particles into indoor environments. *J. Aerosol Sci.* **2005**, *36*, 303−322.
(21) Kittelson, D. B.; Watts, W. F.; Johnson, J. P.; Remerowki, M. L.; Ische, E. E.; Oberdorster, G.; Gelein, R. A.; Elder, A.; Hopke, P. K.; Kim, E.; Zhao, W.; Zhou, L.; Jeong, C. H. On-road exposure to highway aerosols. 1. Aerosol and gas measurements. *Inhalation Toxicol.* **2004**, *16*, 31−39.
(22) Klepeis, N. E.; Nelson, W. C.; Ott, W. R.; Robinson, J. P.; Tsang, A. M.; Switzer, P.; Behar, J. V.; Hern, S. C.; Engelmann, W. H. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J. Exposure Anal. Environ. Epidemiol.* **2001**, *11*, 231−252.
(23) U.S. EPA. *Carbon Dioxide as a Fire Suppressant: Examining the Risks. Appendix B - Overview of Accute Health Effects*; EPA 430-R-00-002; U.S. EPA: Washington, DC, 2000.

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