An Empirical Study of the Impact of Freeway Traffic on in-Vehicle Exposure to Ultrafine Particulate Matter

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ABSTRACT
There is clear evidence of the adverse health impacts of traffic-related ultrafine particulate matter. As more commuters are spending a significant portion of their daily routine inside vehicles it is increasingly relevant to study exposure levels to harmful pollutants. This study is the first research effort to simultaneously link detailed traffic data, traffic video analysis, and in-vehicle ultrafine particulate (UFP) exposure data. The objective is to empirically test relationships between traffic characteristics and UFP exposure concentrations. We also study the impact of vehicle shell effects including windows, ventilation, and air conditioning on UFP levels. The results of statistical tests and analysis show that the vehicle shell is the most important factor for in-vehicle UFP exposure concentrations. Closing the external air intake vent is more than twice as effective as rolling up the windows alone – showing that there are steps individual travelers can take to reduce their exposure. Surprisingly, traffic variables have little significant impact on UFP exposure concentrations. Traffic density is the most significant traffic variable, suggesting that inter-vehicle spacing is more important than changing emissions rates in congestion. Finally, qualitative analysis suggests that heterogeneity in the vehicle fleet is the other major factor influencing variations in exposure concentrations. The results of this research have important implications for exposure modeling and potential exposure mitigation strategies.

INTRODUCTION

Motor vehicle emissions are a known contributor to urban air quality problems [1]. They also have been shown to lead to negative health outcomes for people with long-term exposures, especially to fine particulate matter [2]. These concerns raise interest in strategies to mitigate the health impacts of traffic-related pollution – either by reducing vehicle emissions or reducing human exposure to emissions.

Traffic congestion, in particular, has been cited as a cause of human health problems [3]. Congestion mitigation in general is often cited as an air quality improvement strategy [4]. But the full effects of congestion mitigation on motor vehicle emissions and air quality are not well quantified [5–7]. There is even less research regarding the impacts of congestion and congestion mitigation on human exposure to traffic-related pollution.

The objective of this research is to quantify relationships between freeway traffic characteristics and air quality/exposure for motorists. This will help illuminate potential exposure mitigation strategies by identifying the primary influencing factors. We also aim to identify gaps or misconceptions in our knowledge about the traffic congestion-exposure relationship, which will help to guide future research in this area.

This paper presents results from an ongoing empirical study of traffic conditions and in-road or near-road pollution exposures in Portland, Oregon. We first discuss the background literature and state-of-knowledge regarding the traffic congestion-exposure relationship. We then describe the data collection method. Results are presented next, followed by conclusions and a discussion of future work.

BACKGROUND AND LITERATURE

Ultrafine particles (with diameter <0.1μm) are a main component, in terms of particle number, of motor vehicle emissions. Gasoline and diesel engines produce a significant number of particles in the ultrafine size range, with the majority of particle number for gasoline engine exhaust ranging from 20-60nm and for diesel engine exhaust from 20-130nm [8], [9]. While changes in fuel composition and modern engine technology have led to reductions in vehicle emissions of particles with larger diameters and mass concentration, UFP emissions measured by particle number concentration (PNC) have remained unchanged or even increased [10].

In-roadway concentrations of UFPs are elevated compared to ambient conditions. PNCs are significantly higher adjacent to freeways and can remain significantly greater than background concentrations at distances of 300m away [11–15]. During times of heavy congestion, UFP concentrations have been found to be elevated above background to a region of impact beyond 300m [16]. Evaluation of on-road, in-vehicle particle concentrations has recently begun with a small number of studies [17], [18]. Particle concentrations have been found to vary widely by location or roadway and to be affected by specific vehicular traffic sources like truck traffic density [19]. Due to roadway concentrations many times higher than ambient conditions time spent in a vehicle can contribute a large fraction of total exposure [17], [18], [20].

Health Impacts

Epidemiological evidence shows associations between adverse health effects for populations living in close proximity to traffic-related pollution compared to those living further away. Long-term exposure to traffic-related particulate matter has been associated with pulmonary risks such as asthma development, reduced lung function and growth, increased hospital visits, pulmonary mortality, and a higher prevalence of adverse respiratory symptoms [21]. In a thorough, critical review of epidemiology and toxicology studies involving particulate vehicular emissions, Grahame and Schlesinger [22] found that epidemiology studies with accurate exposure measurement methods show consistent associations between vehicle particulate matter and cardiovascular morbidity and mortality including long-term risks for ischemic heart disease and acute myocardial infarction.

Toxicological studies have shown specific mechanisms by which traffic-related UFP and diesel exhaust particles may cause adverse health responses. The small sizes allow for deep deposition into the lung to the alveolar region, pulmonary interstitial spaces, mitochondria cell level, and passage into the circulatory system [23–25]. Macrophages and other respiratory clearance mechanisms are not effective for UFPs, leaving the respiratory system vulnerable to exposure. The high number and presence of UFPs in the lungs can also cause mechanical damage leading to inflammation and oxidative stress both of which can be precursors to cardiopulmonary health risks. Studies using in-vitro, in-vivo and human panel designs involving particle numbers and diesel exhaust exposures have shown significant results of adverse health impacts, supporting a causal relationship between traffic-related particulate matter and adverse cardiovascular impacts [22].

Short-term exposures, as would be experienced while commuting in traffic, have also begun to show negative health effects tied to traffic-related particulates. The National Human Activity Pattern Survey found an average of 95 minutes per day is spent in-vehicle [26]. Various studies exposing healthy humans to diesel exhaust for approximately a 60-minute exposure found adverse health responses of inflammation and oxidative stress hours after the exposure occurred [27–29]. Time spent in traffic with the use of a car was the most common source of exposure significantly associated with the onset of a first myocardial infarction (MI) (heart attack) [30]. The time spent commuting in the roadway environment with elevated PNCs has direct effects on the blood stream and respiratory system of humans suggesting the need to mitigate in-vehicle exposures to traffic-related particulate matter.

Factors Affecting UFP Exposure in the Transportation Environment

PNCs in the transportation environment are reduced by atmospheric dispersion and dilution through enhanced Brownian coagulation leading to particle size growth [31] or condensation/evaporation to alter particle size, lowering number concentrations [32]. The roadway environment is not homogenous, and characteristics of the roadway and immediate surroundings will affect how much dispersion or dilution can take place.

Driving behavior and individual human receptor factors may also affect exposure. The close proximity of a vehicle to undiluted emissions from other vehicles can elevate in-vehicle exposure [33]. Respiration rate and/or previous health conditions of the driver would affect volumes of pollutants inhaled, absorption, uptake levels, and total exposure levels. Additionally, the seal of the individual vehicle and ventilation types could create different barrier levels changing exposure levels [34]. A recent study of in-vehicle exposure found lower UFP concentrations with the ventilation system set to recirculation and the ventilation fan on high [17].

Traffic Congestion and In-Vehicle Exposure Relationship

In-vehicle exposure assessment studies have traditionally focused on comparing exposure concentrations across travel modes (car, bike, bus, taxi, rail) and types of routes [35]. The impacts of changing traffic conditions on in-vehicle exposure, however, are still not quantified. Real-world data are important to understand the relationships between traffic conditions and in-vehicle exposure due to heterogeneity of the roadway environment. Mobile platform measurements of roadway concentrations have begun to increase in recent years in order to better understand spatial and temporal gradients of air quality in urban areas [19].

While on-road concentrations and in-vehicle concentrations of traffic-related pollution are beginning to be better characterized using real-world data measurement techniques and mobile monitoring, no study has used simultaneous real-world traffic data and pollutant exposure data (outside of video recordings only [18]). This study combines in-vehicle and outside-vehicle UFP measurements with simultaneous traffic data gathered at various levels of traffic congestion. Measurements are used to quantify relationships between freeway traffic congestion characteristics and UFP exposure concentrations for motorists.

DATA COLLECTION

The data collection effort was designed to empirically test relationships between traffic conditions and UFP concentrations. Using probe vehicles in the traffic stream and embedded roadway traffic sensors, we collected concurrent traffic and air quality data on six non-contiguous days during the summer and fall of 2010.Probe vehicle were driven on a 6.4-mile stretch of OR-217, an urban freeway in the Portland, Oregon metropolitan area.

On each day of data collection, a single probe vehicle equipped with air quality instruments, two GPS (Global Positioning System) receivers, and a forward-facing video camera was driven continuously on the freeway for a period of approximately three hours. Simultaneous data were also gathered from vehicle detectors along the freeway and from stationary air quality and meteorological monitoring stations. Three different probe vehicles were used over the six days of data collection (all passenger sedans).

In total, 94 trips were executed, where a “trip” consists of the probe vehicle traveling the 6.4-mile corridor in a single direction. These trips constitute 15.4 hours of data, or 55,543 second-by-second data points. The probe vehicle trips were executed in loops, alternating southbound (SB) and northbound (NB) travel directions. Five of the data collection days were on weekdays (Tuesdays and Thursdays), and one was on a Sunday (to capture lighter traffic conditions). On the weekdays, the data collection periods covered varying time spans before, during, and after the evening traffic peak period.

The simultaneous data collected were:

- Forward-facing digital video recordings from the probe vehicle
- GPS-based speed and position for the probe vehicle (1 second intervals)
- In-vehicle UFP concentrations on both the driver's and passenger's sides (1 second intervals)
- Outside-vehicle UFP concentrations (1 second intervals)
- Traffic data for each lane (vehicle count and speed) from inductive dual-loop detectors (20 second intervals)
- Meteorology from a nearby weather station (10 minute intervals)
- Air quality from regional air quality monitoring stations (Hourly and daily aggregations)
- Road grade and geometry

UFP data were collected on all days but because only two UFP monitors were available, either two in-vehicle monitors or one in-vehicle and one outside-vehicle monitor were used. The 6 data collection days are summarized in Table 1. The weather and air quality data in Table 1 are averaged over the data collection period, with the exception of $PM_{2.5}$ (particulate matter <2.5 microns) and AQI (Air Quality Index) which are daily averages. The data sources are described in more detail below.

Table 1. Data Collection Summary

	June 10, 2010	August 31, 2010	September 2, 2010	September 7, 2010	October 12, 2010	October 17, 2010
Day of Week	Thursday	Tuesday	Thursday	Tuesday	Tuesday	Sunday
Hours	15:00–18:32	14:48–18:02	14:42–17:50	14:27–18:18	15:50–19:18	17:45–20:00
# of Trips	7 SB, 7 NB	7 SB, 7 NB	8 SB, 8 NB	8 SB, 8 NB	9 SB, 9 NB	8 SB, 8 NB
Probe Vehicle	1999 Pontiac Grand Prix	2010 Toyota Prius Hybrid	2010 Toyota Prius Hybrid	2007 Honda Civic Hybrid	2007 Honda Civic Hybrid	2007 Honda Civic Hybrid
OR-217 Traffic Volume (veh/day)	103,259	99,456	103,905	97,678	97,186	72,205
Temperature * (°F)	54	60	81	62	65	54
Wind Speed * (mph)	0.6	1.4	7.3	0.7	0.5	1.2
Wind Gusts * (mph)	4.1	5.7	16.2	3.9	1.5	5.6
Relative Humidity * (%)	97	93	37	80	42	57
Hourly Precip.* (in)	0.02	0.01	0.00	0.06	0.00	0.00
Nitrogen Oxides * (ppb)	13.8	10.9	8.87	13.4	20.2	15.6
Ozone * (ppm)	19.4	21.6	41.8	20.6	14.6	13.4
Carbon Monoxide * (ppm)	0.42	0.30	0.22	0.27	0.35	0.39
$PM_{2.5}$ + ($\mu g/m^3$)	2.6	2.8	3.0	3.6	5.6	7.2
AQI +	8	9	10	12	18	23

* averaged over data collection period; + averaged over entire day

As stated previously, the focus of this study is the relationship between traffic conditions and UFP exposure concentrations. Since some influencing factors on UFP concentrations could not be experimentally controlled (especially relating to pollutant dispersion), our goal was not to seek identical conditions on each data collection day. We sought instead a wide range of traffic conditions and allowed other factors of secondary interest to vary by date (meteorology, background concentrations, starting time, probe vehicle). Thus, during the analysis a single "date" factor is indicative of myriad exogenous influences.

The other varying experimental factor was vehicle ventilation condition. Trips were executed varyingly with the windows up or down, the air vents open or closed (recirculating cabin air), and the air conditioning (A/C) on or off. The A/C "on" was only tested with windows up and vents closed. The "windows down" condition was conducted with three of the four windows open. The fan in the vehicle's ventilation system was set to medium.

Probe Vehicle Data

Three different study vehicles were used, all gasoline-fueled passenger sedans: a 1999 Pontiac Grand Prix, a 2007 Honda Civic (gas-electric hybrid), and a 2010 Toyota Prius (gas-electric hybrid). The vehicles were driven each day by the same driver, using a median-speed driving approach with free choice of lanes. When queues formed on the roadway, the driver maintained a spacing of at least 2 meters from the leading vehicle. A second passenger rode in the back seat of the vehicle, monitoring the data collection equipment. The probe vehicle was equipped with a forward-facing digital video camera in the passenger-side front seat recording images through the front windshield.

Two Garmin iQue® 3600 GPS receivers were used to collect vehicle location and speed data at one-second intervals. A receiver was placed in each of the front and rear windshields. The two data sources were compared and showed good agreement, with a correlation coefficient of 0.998. The final probe vehicle speed and location data were averaged between the two receivers.

In-Vehicle and Outside-Vehicle Air Quality Data

UFP concentrations were measured using two P-Trak ultrafine particle counters (TSI Model 8525). P-Trak instruments are commonly used in personal exposure studies of UFPs for transportation modes because of portability [35]. The P-Trak instrument measures particle number concentrations using condensation with isopropyl alcohol and an optical sensor. Number concentrations are obtained for particles in the range 0.02-1 μm, dominated by the ultrafine size range. The maximum concentration level measured is 500,000 particles per cubic centimeter (pt/cc). The P-Trak instruments were calibrated in October 2009. The instruments were allowed a "warm-up" period of 10 minutes before data collection to avoid possible underestimation bias [36]. A recent study of UFP monitors showed no median bias and median precision of 10% for the P-Trak instruments [36]. When run side-by-side, the two P-Trak instruments used in this study showed good agreement.

The P-Trak instruments were positioned on the back seat of the probe vehicle with inlet tubes connected to the front seat driver-side and passenger-side headrests. These were chosen to approximate the breathing position of vehicle occupants. For outside-vehicle UFP levels, an inlet tube was also fed outside of the sealed passenger-side window. Outside-vehicle concentrations were collected on the last three study days. When outside-vehicle concentrations were collected, the inside-vehicle P-Trak instrument measured passenger-side concentrations only.

Traffic and Roadway Data

Traffic data were obtained from the Portland Oregon Regional Transportation Archive Listing (PORTAL- at www.portal.its.pdx.edu), an archive of transportation data from the Portland-Vancouver metropolitan region. The traffic data were collected by inductive dual-loop detectors with an average spacing of 0.76 miles. Vehicle count and time-mean speed at 20-second intervals were obtained from PORTAL for all study days. The traffic data were matched to the probe vehicle's temporal and spatial position using the in-vehicle GPS data.

The study corridor, OR-217, is a freeway located about 5 miles west of the Portland, Oregon central business district. The speed limit is 55mph and the freeway has 2-3 lanes in each of the NB and SB directions. This freeway had AADT of approximately 100,000 in 2010, with weekday (non-holiday) two-way daily traffic volumes ranging from 95,000 to 107,000 vehicles per day during the months when data were collected. Weekend two-way daily traffic volumes ranged from 59,000 to 92,000 vehicles per day during these months. The daily volumes on the data collection days are included in Table 1. The road grades on the corridor range from 0.2% to 6.2% (positive or negative depending on the direction of travel). These grades were calculated as the average slope between crest and sag vertical curves, with average spacing of 0.43 miles.

From the measured traffic speed, v, in miles per hour (mph) and traffic flow volume, q, in vehicles per hour per lane (veh/hr/ln), traffic density, k, in vehicles per lane-mile (veh/ln-mi) is calculated as $k=q/v$ [37]. Density was not calculated for aggregate average traffic speeds below 7 mph. Level of Service (LOS) is calculated based on traffic density thresholds from the Highway Capacity Manual [38]. LOS is an indicator of traffic congestion level, ranging from free-flow conditions (LOS A) to heavy congestion (LOS F).

Regional Meteorology and Air Quality Data

Meteorology and air quality data were gathered as indicators of the broad weather and background pollution conditions during the study days. Meteorological data (temperature, pressure, humidity, rainfall, and wind) were collected from a permanent weather station approximately 3 miles east of the study corridor. The data were obtained through MADIS (Meteorological Assimilation Data Ingest System) – part of the National Weather Service. Weather measurements were made at approximately 10 minute intervals throughout the study days. Average temperature, wind, relative humidity, and rainfall during the data collection times are shown in Table 1.

Daily particulate air quality data were obtained from the U.S. Environmental Protection Agency's AirData website (http://epa.gov/airdata/). These data were collected at a permanent air quality monitoring station just 1 mile west of the study corridor. The particulate data collected were 24-hour average $PM_{2.5}$and AQI. The AQI is a standardized indicator of air quality, relative to the National Ambient Air Quality Standards (NAAQS). An AQI below 100 indicates concentrations below the NAAQS.

Hour-by-hour air quality data for other pollutants were obtained through the Horizons website (http://horizons.pdx.edu [39]). These data were collected at a permanent air quality station operated by the Oregon Department of Environmental Quality. The station is located approximately 9 miles east of the study corridor. Average concentrations of ozone, nitrogen oxides, and carbon monoxide during the data collection periods are included in Table 1. These average air quality data are intended to serve not as background concentrations, but as indicators of general air quality during the data collection days.

Data from all of the above sources were pulled together and matched based on time stamps and physical location (where appropriate). The joined data were validated using reasonableness checks. Most of the analysis was carried out at 20 second aggregation, matching the resolution of the traffic data. At this aggregation, around 2,800 data points were available for analysis (depending on the variables of interest, because of missing data). The next section presents the results of the data analysis and a discussion of the findings.

RESULTS

This section describes results from analysis of the UFP dataset. We first present an overview of the data, then discuss the relationships between study variables and the measured UFP concentrations inside and outside of the probe vehicle. At 20-second aggregation, the range of observed UFP concentrations inside the vehicle is wide: from 993 pt/cc to 435,250 pt/cc. The passenger-side and driver-side UFP concentrations show good agreement when measured concurrently, with a correlation coefficient of 0.996. The in-vehicle and outside-vehicle UFP concentrations are less strongly correlated, with a correlation coefficient of 0.575. The mean and median passenger-side in-vehicle concentrations are 25,871 pt/cc and 17,628 pt/cc, respectively, with the windows down, and 11,176 pt/cc and 8,661 pt/cc, respectively, with the windows up.

Extreme-Concentration Episodes

There were five observed extreme-concentration episodes with sustained concentrations over 100,000 pt/cc for duration of more than 1 minute (and even reaching the detection limit of 500,000 pt/cc for the second-by-second data). By consulting the video data, an analysis of these periods reveals an individual suspected high-emitting vehicle closely ahead of the probe vehicle during each of these episodes. Suspected high-emitting vehicles are subjectively identified as those with visible emissions (smoke) from the tailpipe, those whose presence correlated with observed foul odors during data collection, and any other heavy-duty vehicles. Three of the suspected high-emitting vehicles are heavy trucks, one is a large passenger pickup truck, and one is a late-model sedan.

Admittedly, the suspected high-emitting vehicle identification process is subjective – but direct measurement of emissions from these vehicles was not possible during our data collection effort. The temporal and spatial correlation of the presence of one of these vehicles with high exposure concentrations makes their emissions a plausible explanation for the high-concentration episodes. A similar effect has been found in previous research efforts [20].

If, indeed, it is individual high-emitting vehicles causing these extreme concentrations, then the heterogeneity of the vehicle fleet is a key factor in varying on-road UFP exposure levels. Measurement of the contribution of individual vehicles to total roadway UFP concentrations is left to future research efforts. In order to look at more generalized traffic relationships with UFP concentrations, time periods with these suspected high-emitting vehicles present are excluded from most of the following analysis. The 5 episodes were each 2-7 minutes in length, resulting in 80 time periods (at 20-second aggregation) identified as having suspected high emitting vehicles. These 80 time periods – 2.85% of the total – are excluded from all but the Analysis of Covariance in the following traffic analysis.

Traffic Conditions and Exposure Concentrations

We next look at relationships between traffic conditions and UFP concentrations. Table 2 shows the number of aggregated observations broken down by traffic Level of Service (LOS) and ventilation conditions. LOS is an indicator of traffic congestion level, calculated from vehicle density as described above. LOS F is the heaviest congestion, while LOS A is the lightest.

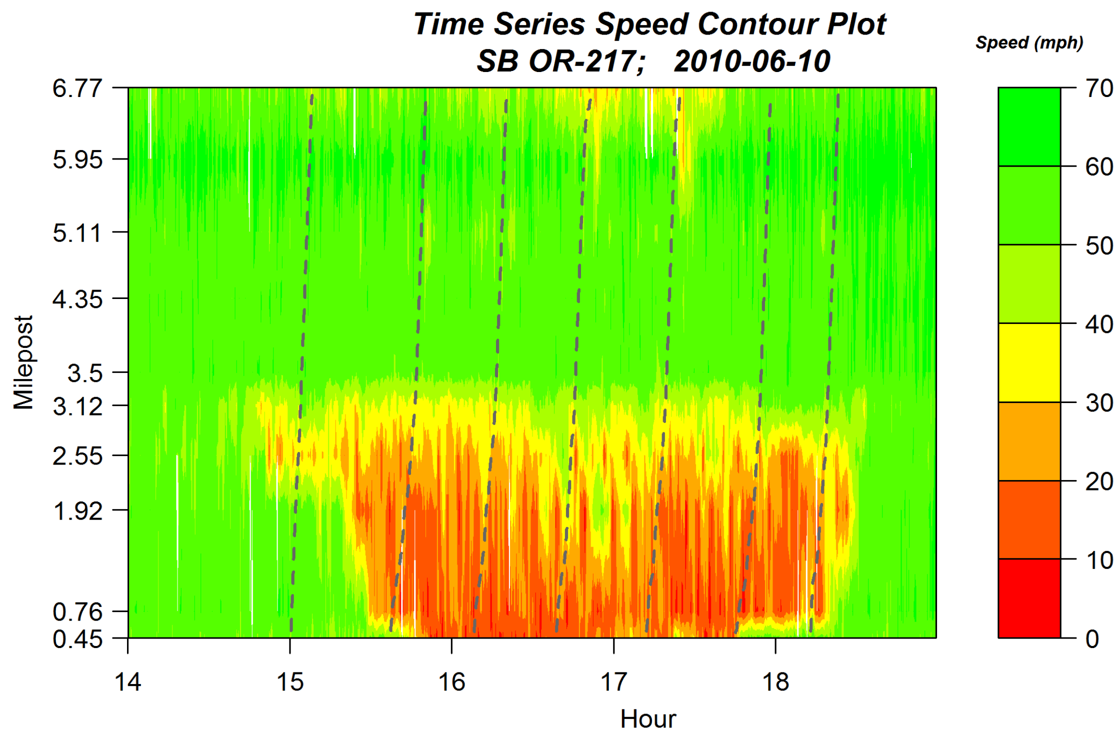
Table 2. Number of 20-second Observations by Freeway LOS and Probe Vehicle Ventilation Condition

	Level of Service (LOS)						
Ventilation Conditions	A	B	C	D	E	F	Total
Windows down, Vent open, A/C off	2	49	152	297	196	525	1,221
Windows down, Vent closed, A/C off	0	1	8	36	26	41	112
Windows up, Vent open, A/C off	23	81	120	158	130	193	705
Windows up, Vent closed, A/C off	14	59	116	115	47	110	461
Windows up, Vent closed, A/C on	1	2	23	69	46	153	294
Total	40	192	419	675	445	1,022	2,793

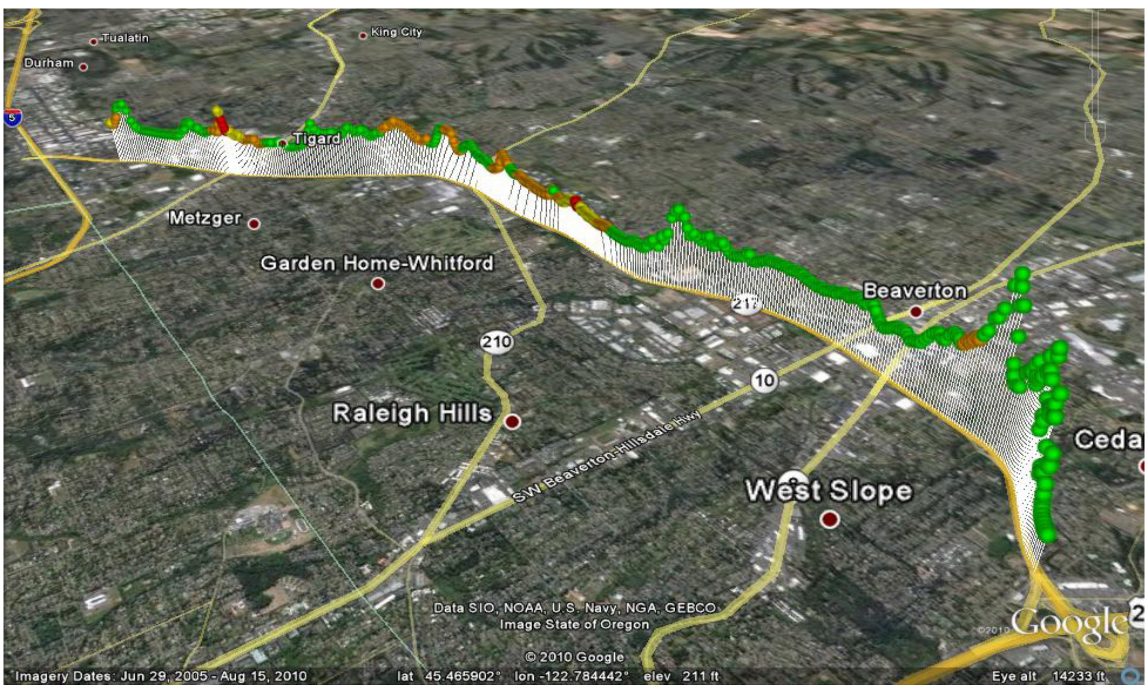
Figure 1(a) sets the probe vehicle data into context by overlaying probe vehicle trajectories and roadway-based traffic speeds on the space-time plane (for southbound trips on June 10^{th}). The colored shadings show the 20-second aggregated traffic speeds based on PORTAL loop detector data (interpolated between detector locations) – white indicates missing data. The dashed lines trace the probe vehicle trajectory as it traverses the corridor.

Figure 1(b) illustrates combined UFP and speed data from a sample probe vehicle trip – this is the 6^{th} trip on September 2^{nd}, a northbound trip with the windows down, the vent open, and the A/C off. The vehicle traveled from left to right in the figure. The probe vehicle speed is indicated by the marker color - with a scale as shown in Figure 1(a) - and the passenger-side UFP concentration is indicated by the height of the markers. In this sample trip, we see that higher concentrations are not aligned with the slower-speed periods.

The lack of correlation between UFP concentration and traffic or vehicle speed is consistent across trips. A comparison of measured UFP concentrations to several traffic variables reveals no clear relationship. Neither in-vehicle nor outside-vehicle UFP concentrations correlate with traffic volume, density, or speed (as measured by PORTAL or the probe vehicle): all have correlation coefficients between -0.07 and 0.07.



(a)



(b)

Figure 1. (a) Sample probe vehicle trips as dashed lines and traffic speeds as colors on the space-time plane and (b) a data collection trip with speed represented as color and in-vehicle UFP concentration as height (map image from *Google Earth*)

Figure 2 shows boxplots of outside-vehicle UFP concentrations segmented by traffic LOS, with suspected high-emitting vehicle episodes excluded. The boxplots show the range, upper/lower quartiles, and median observed values, with statistical outliers as circles. Figure 2 also includes the number of 20-

second aggregation intervals included in the plot for each LOS (as "N") – note that outside-vehicle concentration data were not collected during all time periods.

As can be seen in Figure 2, outside-vehicle concentrations do not notably trend up or down with LOS. Using a non-parametric Wilcoxon signed-rank test to compare each LOS in Figure 2 with its neighbors, only the LOS E versus LOS F comparison is statistically significantly different at p=0.01. Observe that here the difference is *lower* concentrations at the heavier congestion level – and that the difference in means is small compared to the range of concentrations observed. The same lack of relationship is observed in similar comparisons using traffic speed and volume (excluded for brevity).

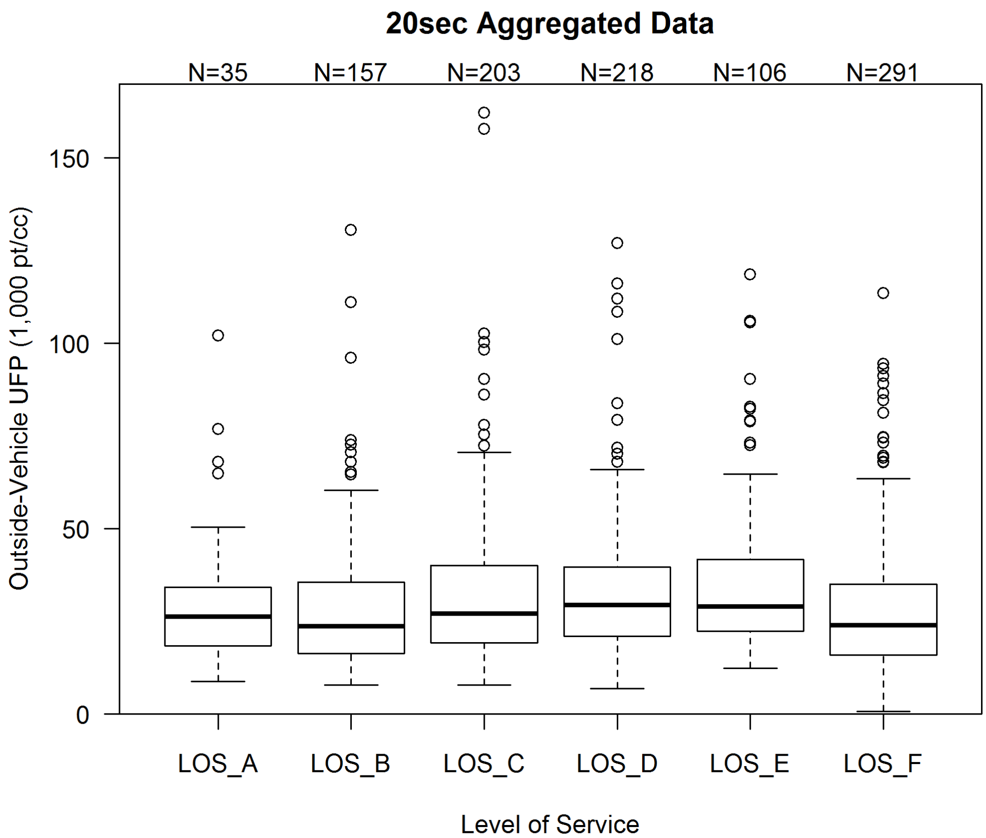


Figure 2. Comparisons of traffic LOS and outside-vehicle UFP concentrations (suspected high emitting vehicle episodes excluded)

Vehicle Ventilation and Exposure Concentrations

In addition to varying traffic conditions, the vehicle ventilation conditions were varied during data collection. Figure 3 illustrates the observed effects of ventilation conditions on in-vehicle UFP concentrations. In Figure 3, data from 4 sample trips with varying ventilation are shown: in-vehicle UFP, outside-vehicle UFP, and probe vehicle speed (as the color of the circles, with a scale as shown in Figure 1) at 20 second aggregations. On the top left, the trip with the most ventilation (windows down, vent open) had the most agreement between in-vehicle and outside-vehicle concentrations. On the top right, we see that rolling up the windows (but leaving the vent open) reduced the in-vehicle concentration compared to the outside-vehicle concentrations, but that the two still generally moved together. The bottom two panels in Figure 3 show that with the windows up and the vent closed, in-vehicle UFP concentrations are unresponsive to outside-vehicle concentrations. Furthermore, when the A/C is "on" the in-vehicle UFP concentrations are slightly lower.

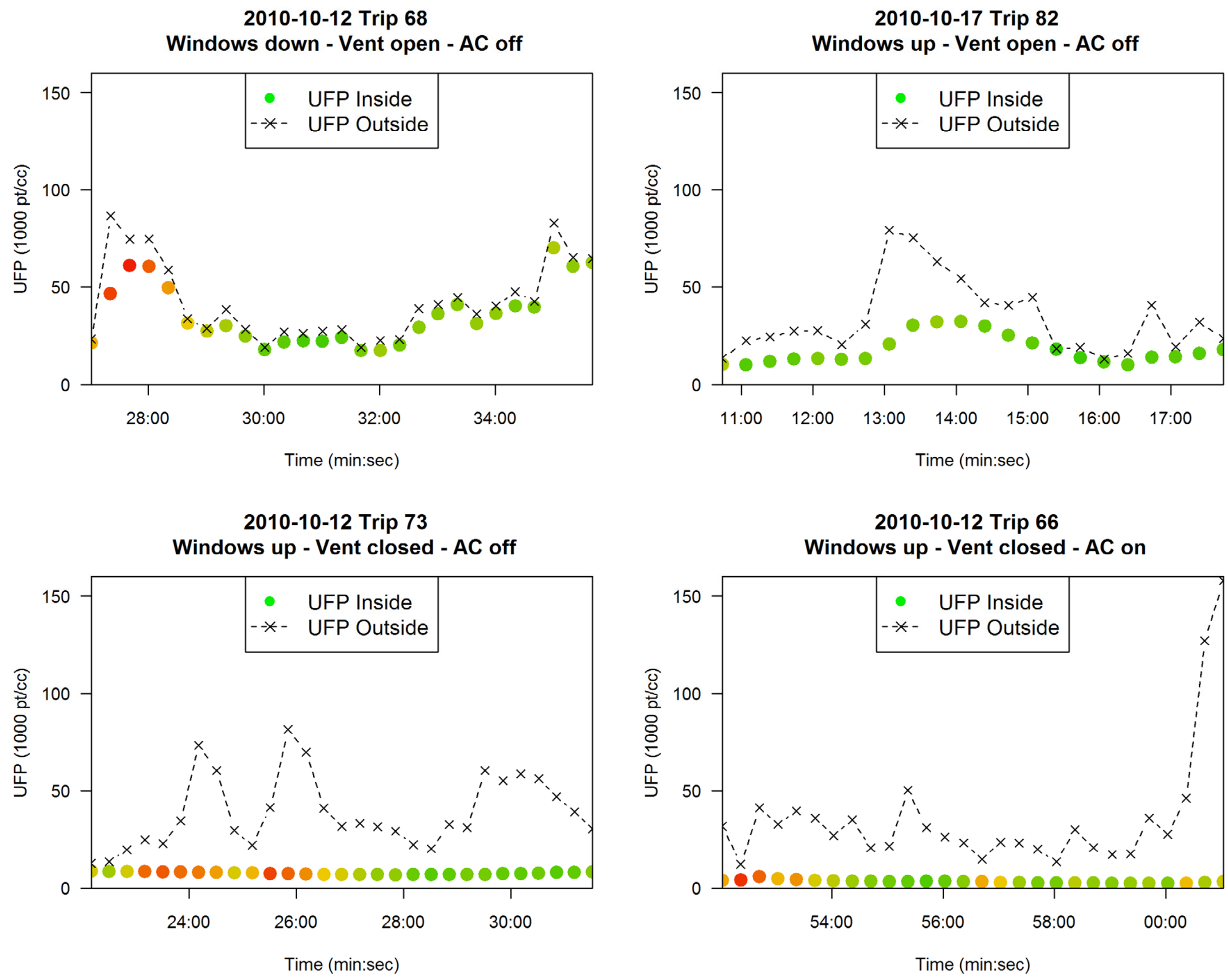


Figure 3. UFP concentrations from sample trips for different ventilation conditions

Combining the traffic and UFP data with ventilation conditions, Figure 4 shows log-transformed in-vehicle UFP concentrations versus probe vehicle speed segmented by ventilation condition at 20-second aggregations (excluding suspected high-emitting vehicle episodes). The windows "up" condition has lower in-vehicle concentrations, which are further lowered when the vents are closed. The effect holds across the range of observed speeds, with the possible exception of very low-speed conditions (below 5 mph), of which there are few observations at this aggregation. In agreement with the previous analysis of outside-vehicle concentrations, the in-vehicle concentrations do not trend with speed.

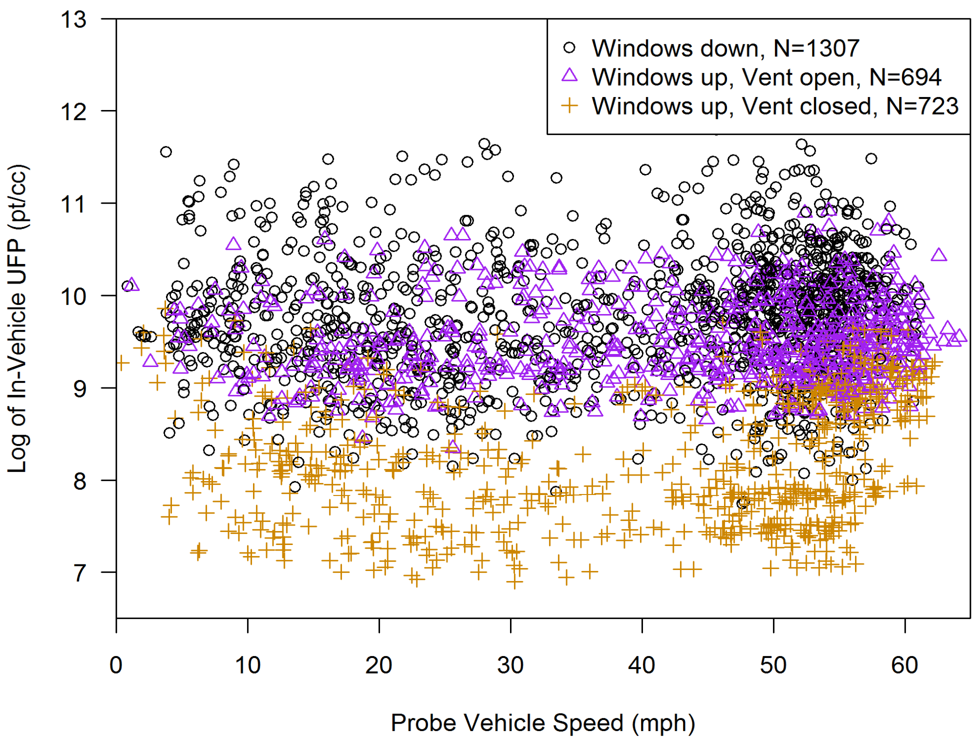


Figure 4. Log-transformed 20-second UFP concentrations versus speed, by ventilation conditions (suspected high emitting vehicle episodes excluded)

The vehicle ventilation condition also affects the concentration variability, in addition to the mean values. Looking at longer intervals, Figure 5 shows boxplots of UFP peaking at 1-minute aggregations (calculated as the 90th percentile concentration divided by the mean concentration for the time interval). The figure is segmented with the first three boxplots showing in-vehicle UFP peaking for different vehicle ventilation conditions and the fourth boxplot showing outside-vehicle UFP peaking. The outside-vehicle UFP peaking is the highest, and similar to the in-vehicle UFP peaking with the windows down. The in-vehicle UFP peaking with the windows up is much lower, and lower still when the vents are closed. Again using a non-parametric Wilcoxon signed-rank test to compare the peaking distributions, all conditions are statistically significantly different at $p=0.01$. Rolling up the windows and closing the vents has a damping effect on the UFP concentrations, in addition to the mean-reducing effect shown in Figure 4.

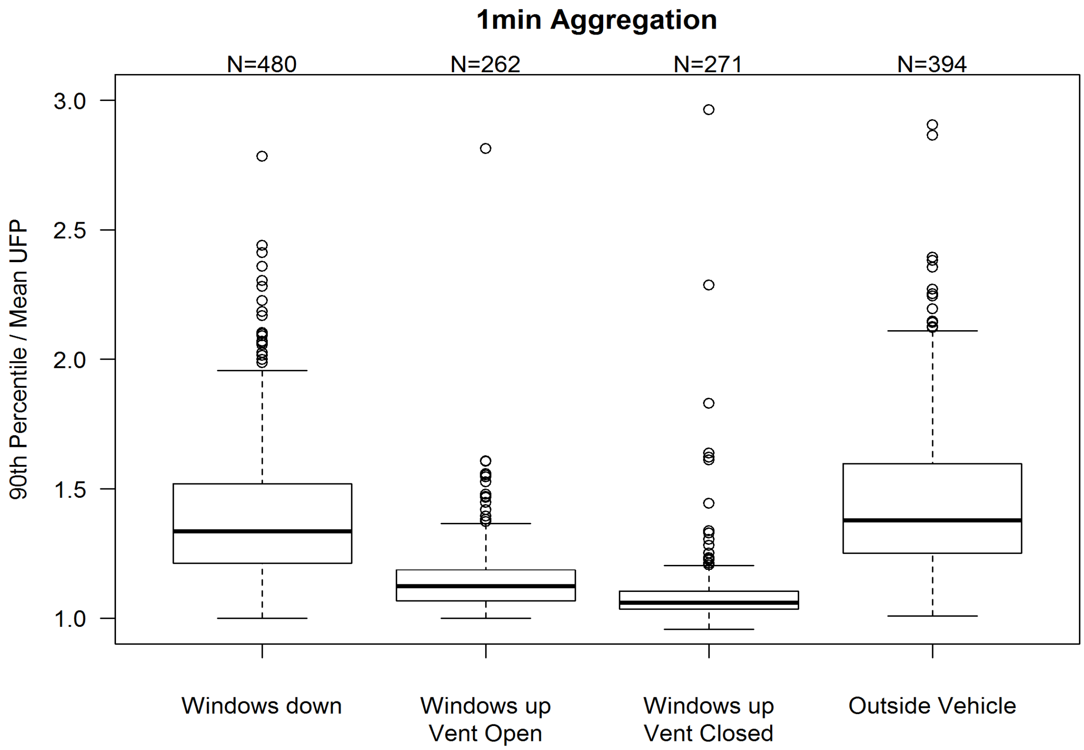


Figure 5. UFP concentration peaking and ventilation conditions

In/Out-Vehicle Concentration Comparison

We next compare the in-vehicle to outside-vehicle UFP concentrations for different ventilation conditions. Figure 6 shows the ratio of in-vehicle to outside-vehicle UFP concentrations versus probe vehicle speed at 20-second aggregations, segmented by vehicle ventilation. Again, suspected high-emitting vehicle episodes are excluded. A value of one indicates equal concentrations inside and outside of the vehicle. As can be expected from preceding results, closing the windows and vents shields the inside of the vehicle from elevated outside-vehicle concentrations. The effect holds at varying vehicle speeds. Even with the windows down, the vehicle shell provides some protection from outside-vehicle UFP concentrations (the in/out vehicle UFP ratio is mostly below one).

All ventilation conditions had some observations with in/out UFP ratios above one, indicating higher in-vehicle concentrations than outside-vehicle concentrations. This is more likely due to time series effects (lags in concentration spikes) than to inside-vehicle sources of UFP (see [17]). A few observations show much higher in-vehicle concentrations than outside-vehicle concentrations (for speeds below 5 mph with the windows and vents closed). These observations could be indicative of low ventilation conditions that prevent clearing of UFP that previously entered the vehicle cabin. There could also be vehicle proximity effects in low-speed queues, where inter-vehicle spacing is smaller. A thorough investigation of UFP penetration of vehicle cabins in low-speed queues is left as a topic for future research.

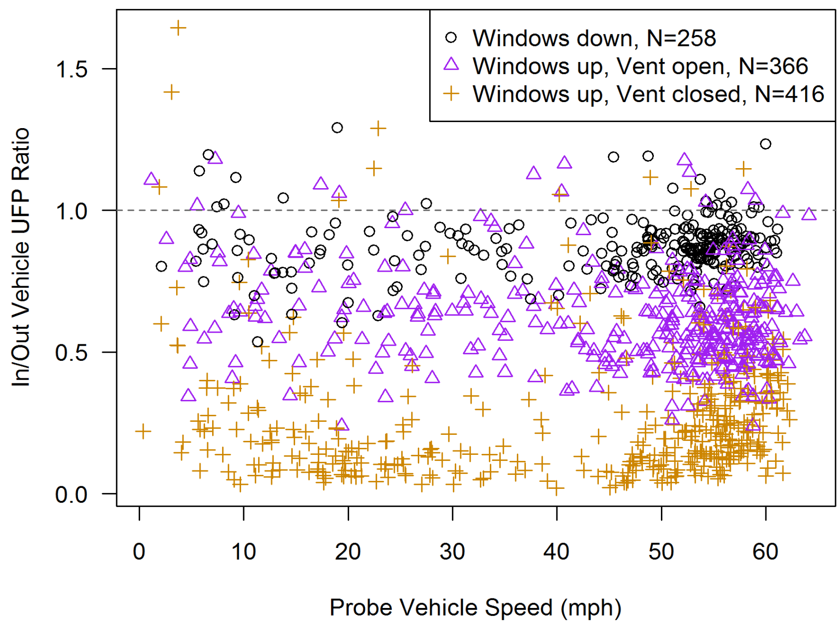


Figure 6. In/out-vehicle UFP concentration ratios versus speed at 20-second aggregation (suspected high emitting vehicle episodes excluded)

Regressing in-vehicle concentrations on out-vehicle concentrations by ventilation type produces variable coefficients of 0.822, 0.360, and 0.036 for Windows down, Windows up-Vent open, and Windows up-Vent closed conditions, respectively (all statistically significant at p=0.01). This indicates that in-vehicle concentrations increase at about 82% of the increase in outside-vehicle concentrations with the windows down. With the windows up, in-vehicle concentrations increase at 36% of the increase in outside-vehicle concentrations with the vents open and 4% of the increase in outside-vehicle concentrations with the vents closed.

In order to test the possibility of intrusion of UFP from probe vehicle emissions into the vehicle cabin, in-vehicle UFP were measured with the engine off and on (idling) at a location away from other motor vehicle activity (at a probe vehicle speed of zero). No observable change in UFP concentrations was observed with the engine idling as compared to off, indicating that the role of the probe vehicle's emissions in influencing in-vehicle exposure concentrations is likely small for this study. This issue, however, is left as a topic for future research on varying vehicle types.

Analysis of Covariance

As a final analysis step we perform an analysis of covariance with in-vehicle passenger-side UFP concentrations as the dependent variable. The UFP concentrations are log-transformed because of their strong positive skew. The independent variables are Date (dummy), presence of a suspected high-emitting vehicle (dummy), relative humidity at stationary weather station (%), road grade (%), ventilation conditions (4-factor dummy: windows down, windows up-vent open, windows up-vent closed-A/C off, and windows up-vent closed-A/C on), and one of three traffic variables (traffic volume in vehicles per hour, traffic density in vehicles per lane-mile, or probe vehicle speed in miles per hour).Statistical significance is accepted at p=0.01. Only one weather variable was selected because of relationships with other weather variables. Similarly, only one traffic variable at a time is used because of fundamental traffic flow relationships (see [37]).

Analysis of covariance results are shown in Table 3 for three different models (each using a different traffic variable). The top part of Table 3 shows the change in sum of square error (SS) that results from dropping each variable from the model, and the F statistic associated with dropping the model variable. Statistical significance of the F statistics is indicated by the number of stars, with p-values indicated in the bottom of the table. The bottom part of Table 3 shows the estimated coefficients associated with the analysis of covariance, along with t statistics and an associated statistical significance (again, see the p-values at the bottom of the table).

Table 3. Analysis of Covariance

	Df	SS	F		SS	F		SS	F	
Date	5	246.7	121.0	***	251.2	123.4	***	251.7	125.5	***
Suspected High Emitter	1	272.3	667.9	***	267.3	656.5	***	269.5	671.9	***
Humidity (%)	1	5.1	12.4	***	4.9	12.0	***	4.0	9.9	**
Grade (%)	1	1.3	3.1	*	1.8	4.5	*	2.9	7.3	**
Ventilation	3	952.8	778.9	***	952.1	779.4	***	965.0	802.1	***
Volume (veh/hr)	1	0.4	0.9	.	-	-		-	-	
Speed (mph)	1	-	-		1.9	4.7	*	-	-	
Density (veh/ln-mi)	1	-	-		-	-		3.7	9.2	**
Residual SS[a]	2791	1038.0			1136.5			1106.0		
Total SS[a]		2569.5			2569.5			2550.9		

[a] 33 observations excluded from the third model (due to missing traffic density data)

	Coef.	t		Coef.	t		Coef.	t	
Constant	8.951	48.7	***	9.076	52.6	***	8.981	52.3	***
Date									
2010-08-31	0.091	2.1	*	0.083	2.0	*	0.086	2.1	*
2010-09-02	0.332	2.8	**	0.337	2.8	**	0.309	2.6	**
2010-09-07	0.402	6.5	***	0.406	6.7	***	0.393	6.5	***
2010-10-12	1.038	14.2	***	1.045	14.4	***	1.030	14.2	***
2010-10-17	0.794	8.5	***	0.808	8.9	***	0.799	8.8	***
Suspected High Emitter	1.913	25.8	***	1.901	25.6	***	1.909	25.9	***
Relative Humidity (%)	0.006	3.5	***	0.006	3.5	***	0.005	3.1	**
Grade (%)	0.010	1.8	.	0.012	2.1	*	0.015	2.7	**
Ventilation									
windows up, vent open, A/C off	-0.401	-10.2	***	-0.404	-10.3	***	-0.398	-10.1	***
windows up, vent closed, A/C off	-1.302	-34.3	***	-1.299	-34.3	***	-1.309	-34.7	***
windows up, vent closed, A/C on	-2.125	-39.5	***	-2.144	-39.3	***	-2.166	-40.0	***
Volume (veh/hr)	0.00001	0.9		-	-		-	-	
Speed (mph)	-	-		-0.00177	-2.2	*	-	-	
Density (veh/ln-mi)	-	-		-	-		0.00171	3.0	**
Adjusted R^2	0.555			0.556			0.565		

. = p<0.1, * = p<0.05, **=p<0.01, *** = p<0.001

The results shown in Table 3 are consistent with the preceding analysis. Ventilation is the most important factor, explaining about 37% of the null deviance. Date and Suspected high-emitting vehicle are the next most important factors, explaining 10-11% of the null deviance, each. All three variables are highly significant. Humidity, Grade, and all three traffic variables have much lower explanatory power, with a change in sum of square error of less than 1% associated with their presence in the model. Thus, while the variables are statistically significant, they have a small impact on expected UFP concentrations.

The coefficient estimates in Table 3 are in line with expectations. High-emitting vehicles are associated with a large increase in UFP concentrations, as are certain data collection days. UFP concentrations are increasingly reduced by rolling up the windows, closing the vents, and turning on the A/C. Grade and Humidity are each associated with small increases in in-vehicle UFP concentrations. The traffic variables have small impacts on UFP concentrations as well. Concentrations are expected to increase slightly with traffic volume and density, but decrease slightly with speed.

At the observed traffic volumes of 1,000 to 5,000 veh/hr, the impact of varying traffic volumes on UFP concentrations is expected to be small (less than 4%). Similarly, a 10 mph increase in speeds is associated with about a 2% reduction in UFP concentrations. Over a range of density from 10 to 100 veh/ln-mi, UFP concentrations are expected to change by about 15%. Thus, density is the most significant traffic variable (though still much smaller than other factors such as date, ventilation, and suspected high-emitting vehicles).

The Date dummy variable is intended to capture multiple exogenous influences such as probe vehicle, weather-based dispersion effects, and background concentrations. The last two dates had the highest associated base UFP concentrations and the first two the lowest. This trend is partially reflected in the daily background $PM_{2.5}$ concentrations (see Table 1). The daily weather variables are correlated, so it is possible that the influences of changing wind, temperature, and rain conditions on UFP concentrations are reflected in the Humidity variable rather than the Date variable.

CONCLUSIONS

This paper presents results from an empirical study of in-vehicle exposure to ultrafine particulate matter for motorists in freeway traffic. The objective is to empirically test relationships between traffic characteristics and UFP exposure concentrations. Although recent research has shown that traffic congestion has a relatively low impact on total emissions [40], the results presented in this research are even clearer: in terms of in-vehicle UFP exposure and concentrations, traffic variables have little impact. Comparing among traffic variables, density is the more significant, while traffic volume is not significant and vehicle speed is somewhat significant. This suggests that the influence of traffic congestion on UFP exposure concentrations is primarily through an increase in the proximity of motorists to vehicle emissions sources, rather than through increased vehicle emissions.

The results of statistical tests and analysis presented in this paper show that the vehicle shell is the most important factor for in-vehicle UFP exposure concentrations. Closing the external air intake vent is more than twice as effective as rolling up the windows alone. These barriers reduce both mean concentrations and short-duration high-concentration spikes (though the health implications of this are not yet known). Turning on the A/C appears to further reduce in-vehicle UFP concentrations, possibly by accelerating the agglomeration process.

Although it could not be measured, qualitative analysis suggests that heterogeneity in the vehicle fleet is the other major factor influencing variations in exposure concentrations. The presence of individual suspected high-emitting vehicles correlated with extremely high excursions in exposure concentrations. This has several implications. The first is that on-road air pollution exposure modeling can only estimate highly aggregate exposure levels unless fleet heterogeneity is modeled. Second, in support of the findings above related to traffic density, fleet heterogeneity means that inter-vehicle spacing is an important consideration for exposure concentrations of short-lived air pollutants such as UFP. Finally, in terms of mitigation strategies, targeting individual high-emitting vehicles could be more effective than general congestion relief or traffic flow improvements for reducing on-road UFP exposure.

To the best of our knowledge, this is the first study that combines UFP in-vehicle exposure measurements with simultaneous detailed traffic data. As such, there are still many aspects that require further study. Future research efforts should address the potential impacts of a few high-emitting vehicles on total motorist exposure, the penetration of UFP into a vehicle cabin for different vehicles and driving conditions, and the effect of vehicle proximity on UFP concentrations in low-speed queues. Also, plans are currently underway to conduct a similar study on an urban arterial roadway.

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