Air Quality at Bus Stops

Empirical Analysis of Exposure to Particulate Matter at Bus Stop Shelters

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Congested traffic corridors in dense urban areas are key contributors to the degradation of urban air quality. While waiting at bus stops, transit patrons may be exposed to greater amounts of vehicle-based pollution, including particulate matter (PM), because of their proximity to the roadway. Current guidelines for the location and the design of bus stops do not take into account air quality or exposure considerations. This study compared the exposure of transit riders waiting at three-sided bus stop shelters that either faced the roadway traffic or faced away from the roadway traffic. Shelters were instrumented with air quality monitoring equipment, sonic anemometers, and vehicle counters. Data were collected for 2 days at three shelters during both the morning and the afternoon peak periods. Bus shelter orientation was found to significantly affect concentration of four sizes of PM: ultrafine particles, PM_1, $PM_{2.5}$, and PM_{10}. Shelters with an opening oriented toward the roadway were consistently observed to have higher concentrations inside the shelter than outside the shelter. In contrast, shelters oriented away from the roadway were observed to have lower concentrations inside the shelter than outside the shelter. The differences in PM concentration were statistically significant across all four sizes of particulate matter studied. Traffic flow was shown to have a significant relationship with all sizes of particulate concentration levels inside bus shelters. Microscale anemometer measurements were made next to bus shelters. Both wind speed and direction were shown to affect particulate concentrations differently, depending on shelter orientation.

Commuters in the United States spend an average of 45 min per day traveling to and from work (*1*). Concerns over traffic congestion, public health, and environmental deterioration have fostered policies to shift from the use of single-occupancy vehicles to nonautomotive or public transport modes of travel in an effort to reduce congestion and improve public and environmental health while maintaining mobility. Exposure to air pollution on and near the roadway varies with mode choice: single-occupancy vehicle, carpool, public transportation, walking, or bicycling. Research has shown that drivers inside a vehicle with windows up and vents closed are exposed to significantly lower levels of pollution. However, public transportation users waiting at stops are not protected by the vehicle shell and may be exposed to significant amounts of pollution, including particulate matter (PM), as a result of waiting for buses near busy corridors. However, transit user exposure at bus stops has not been properly addressed in the literature.

PM is one of six common air pollutants regulated by the National Ambient Air Quality Standards (NAAQS), established by the U.S. Environmental Protection Agency (EPA) as part of the 1990 Clean Air Act (*2*). PM is a complex mixture of solid and liquid material, made up of carbon particles, hydrocarbons, and inorganic materials. PM is unsafe at any exposure level, meaning that there is no particle concentration threshold below which human health is not jeopardized (*3*). PM is generally classified into four categories based on the aerodynamic diameter of the particles. PM_{10} (coarse particles), $PM_{2.5}$ (fine particles), and $PM_{1.0}$ (very fine particles) are defined as having aerodynamic diameters less than 10 μm, 2.5 μm, and 1.0 μm, respectively.

$PM_{0.1}$, more commonly known as ultrafine particles (UFP), have a diameter of less than 0.1 μm and are the smallest particles yet classified. UFP dominate the particulate number spectrum yet make up a very small percentage of total particulate mass; as a result, UFP are characterized by particle number (particles/cm^3) as opposed to particle mass (mg/m^3 or μg/m^3) for $PM_{1.0}$ and larger. Ambient PM_{10} background concentrations, unaffected by roadway sources, range from 17 to 61 μg/m^3 (*4*). Ambient $PM_{2.5}$ background concentrations are generally below 16 μg/m^3 (*5*). Ambient urban UFP background concentrations range from a few thousand to 20,000 particles/cm^3 (*3*). NAAQS exposure standards were most recently revised in 2006 to tighten the 24-h $PM_{2.5}$ standard to 35 μg/m^3, whereas the 24-h PM_{10} standard has remained at 150 μg/m^3 since 1997. $PM_{1.0}$ and UFP exposure standards have not yet been established by EPA.

Although EPA bases its air quality standards on annual and 24-h exposures, it is thought that peak exposures (1 h or less in duration) are the most relevant to human health and exacerbate the symptoms of existing respiratory conditions such as asthma (*6*).

Much attention has been given to the epidemiological association between exposure to PM and adverse health outcomes (*3, 7–9*). PM exhibits gaslike properties and inhalation brings the particles deep into the lungs. The body's natural defenses, such as nasal hair filtering and cilia in the lungs, are unable to capture PM because of the small size of the particles (*10*). PM has been linked to aggravation of asthma, chronic bronchitis, and decreased lung function (*10*). Many studies have documented negative cardiovascular effects from exposure to PM_{10} and $PM_{2.5}$ (*11, 12*), and $PM_{1.0}$ and UFP have been shown to increase cardiorespiratory symptoms for elderly patients (*13*).

Individuals traveling within transport microenvironments may be exposed to higher levels of pollution, thus making up a significant percentage of their daily total exposure within a short amount of time (*14, 15*). Elevated concentrations of PM near roads in excess

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of ambient urban concentrations indicate a direct relationship to vehicle emissions (*16*). Motor vehicles are the primary source of fine particles and UFP along transportation corridors (*17*). Diesel vehicles are one of the largest sources of PM (*2*). PM is a primary emission from diesel engines, and at times diesel engines may emit 10 to 100 times more PM mass than gasoline engines do (*10, 16, 18*).

Exposure to pollutants in transportation microenvironments is often more complex than ambient conditions from a fixed monitoring station (*19*). Fixed monitoring stations have traditionally been used for the establishment of air quality guidelines and policy (including EPA guidelines), but these stations are not designed to represent microscale impacts and as a result may not adequately describe small-scale conditions in close proximity to traffic (*15, 19*). Gulliver and Briggs found a fixed monitoring station to be a poor marker for PM_{10} concentrations 1 km away from their sampling location (*15*). UFP concentrations in particular decrease substantially with distance because of dispersion and coagulation into larger particles, returning to background levels around 300 m downwind from the roadway (*20*). Relatively small barriers, such as parked vehicles, can significantly affect UFP levels (*21*). Therefore, a fixed monitoring station would be expected to underestimate UFP concentration levels for a roadway located outside the 300-m range. Microscale exposure measurements resolve coagulation problems and present a more accurate picture of roadway air quality conditions (*14*).

Several studies have used microscale measurements to investigate commuter exposure to PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ among different commuting modes, including private vehicle, bicycle, walking, and public transportation. The general consensus is that particulate exposure is greatly affected by the mode of transport (*14, 22–24*). Public transportation exposure studies commonly focus on diesel buses, the most common vehicle used by most transit agencies. Buses have repeatedly been singled out as significant sources of PM in urban areas (*14, 25–27*). A common study design involving diesel buses focuses on in-vehicle exposure of bus drivers and bus patrons. In their multimodal study, Adams et al. observed consistent mean in-cabin $PM_{2.5}$ concentrations in the summer (39 $\mu g/m^3$) and the winter (38.9 $\mu g/m^3$) (*28*). Zhu et al. examined the microenvironmental conditions in Harvard University shuttle system buses in Cambridge, Massachusetts (*29*). Concentration levels of PM_{10} ranged from 11 to 18 $\mu g/m^3$, depending on the sample date. Likewise, concentration levels of $PM_{2.5}$ and UFP ranged from 11 to 15 $\mu g/m^3$ and 40,000 to 57,000 particles/cm^3, respectively. Zhu et al. note that $PM_{2.5}$ concentrations were an order of magnitude higher during peak hours, attributed by the authors to high traffic conditions (*29*).

Most reviewed study designs, particularly transit-oriented studies, fail to capture the exposure for a transit patron waiting at a bus stop. Bus stop location is considered to be one of the most important aspects of transit route design, determining transit system performance, traffic flow, safety, and security (*30*). Bus stops are located in one of three configurations, each relative to the closest intersection: nearside, farside, and midblock (Figure 1). Nearside bus stops are located immediately before an intersection in the direction of travel. Farside bus stops are located immediately after an intersection in the direction of travel. Midblock bus stops are located within the block. Shelters are most commonly installed on high-ridership routes or near transfer points or popular destinations. Shelters are commonly made of Plexiglas panels with metal support frames. The arrangement of panels can be used to characterize the shelter. For instance, shelters may be grouped according to the number of panels used to construct the longest solid wall. Orientation of a shelter is characterized by the direction in which the opening faces; the orientation of the shelter is at the discretion of the transit agency.

Only one identified study has evaluated air quality specifically at and within bus stop shelters. Hess et al. evaluated commuter exposure to $PM_{2.5}$ for passengers waiting at seven bus stop shelters in Buffalo, New York, finding that time of day, passenger waiting location, land use, and presence of cigarette smoke have a statistically significant effect on $PM_{2.5}$ concentrations (*31*). Inside the bus shelter, $PM_{2.5}$ levels were measured at 16.24 $\mu g/m^3$ and outside, levels were measured at 14.72 $\mu g/m^3$. A model developed for the study suggests an 18% increase in $PM_{2.5}$ inside a bus shelter versus outside the shelter. The study design, however, leaves room for further investigation. Hess et al. observed morning levels that were higher than evening levels but did not note if this difference may have been due to directional flow of commuter traffic (*31*). Longer sample durations could provide insight into morning and evening peak-hour fluctuations. Only one type of shelter design was studied: shelters that faced toward the roadway. The literature review for the current study was unable to find a published study that has examined differences in shelter orientation with a focus on air quality concerns.

DATA COLLECTION AND EXPERIMENTAL DESIGN

Shelters and Roadway

Bus shelters selected for this study are located along Powell Boulevard, a major east–west arterial located approximately 2 mi east of the central business district of Portland, Oregon. Powell Boulevard serves as a commuter thoroughfare for the outlying suburbs, with high inbound morning traffic volumes and high outbound evening traffic volumes. Land use along the corridor is primarily one- and two-story commercial buildings, apartment complexes, and other uses such as high schools and recreational activities.

There are 31 bus stops along the 2-mi stretch of roadway selected for analysis. Of these 31 stops, 17 feature shelters. The shelters can be of four different configurations, determined by panel layout. Panels that form an opening facing the roadway are described as oriented toward the roadway. Similarly, panels that form an opening facing away from the roadway are described as oriented away from the roadway. Shelters are characterized according to the number of panels in their design, the depth of the shelter, and the orientation of the shelter.

Figure 1 details the built environment surrounding the shelters. The shelter at Location 1 is oriented away from the roadway whereas the shelters at Locations 2 and 3 are oriented toward the roadway. Characteristics of the shelters and roadway are summarized in Table 1. Each shelter is located at a signalized intersection.

Sampling and Instrumentation

PM concentrations were monitored both inside and outside the shelter simultaneously to control for any changes in environmental conditions. Measurements of $PM_{1.0}$ and PM_{10} were made with two DustTrak DRX aerosol monitors (TSI Model 8533). DustTrak monitors have a resolution of ±0.1% of reading or 0.001 mg/m^3, whichever is greater. Both units were calibrated to a zero filter before each use. UFP measurements were made with two P-Trak UFP counters (TSI Model 8525), capable of measuring concentrations between zero and 5×10^5 particles/cm^3 and particle sizes between 0.02 and 1 μm in diameter. The DustTraks and P-Traks

FIGURE 1 Built environment characteristics for (*a*) Location 1 (nearside, facing away from traffic), (*b*) Location 2 (nearside, facing toward traffic), and (*c*) Location 3 (farside, facing toward traffic).

TABLE 1 Detailed Shelter and Roadway Characteristics

Shelter Characteristic	Location 1 (facing away from roadway)	Location 2 (facing toward roadway)	Location 3 (facing toward roadway)
Nearside or farside	Nearside	Nearside	Farside
Eastbound or westbound on Powell	Westbound (inbound)	Westbound (inbound)	Eastbound (outbound)
Distance to curb (m)	0.60	2.74	3.81
Distance to intersection (m)	7.3	3.7	21
Built environment behind shelter	Multistory building, 3.60 m behind shelter	Multistory building, 6.10 m behind shelter	Multistory building, 1.00 m behind shelter
Annual average daily traffic (2009)	35,300	31,500	34,100
Percentage of trucks, morning[a]	12.4	18.6	4.5
Percentage of trucks, evening[a]	9.7	17.1	5.5
Approximate bus headway, morning (min.)	8	8	20
Approximate bus headway, evening (min.)	15	15	7
Average no. of boardings, morning	1.2	1.0	1.9
Average no. of boardings, evening	1.6	1.9	2.8

[a]Trucks = vehicle length > 6 m.

were started simultaneously and operated continuously at 1-s resolutions for the whole sampling period. Before data collection, both sets of instruments were run side by side in the laboratory to ensure that measurements were highly correlated ($r^2 = .996$).

Device intake points were set at 1.5 m above the ground, following standard practice observed in similar studies (*15, 28, 31, 32*). Inside the shelter, intake points were placed in the center of the shelter, approximately 15 cm from the rear panel (referred to as "inside location"). Outside the shelter, intake points were placed 0.9 m from the shelter, mimicking the distance set by Hess et al., at the same distance from the curb as the monitors inside the shelter (referred to as "outside location") (*31*). Devices were randomly rotated between inside and outside locations at the beginning of each sampling period (morning and afternoon periods).

Wind speed and direction in urban settings can have a significant effect on micromeasurements of air quality. To control for these effects, wind speed and direction were measured with an RM Young ultrasonic anemometer (Young Model 81000) placed next to the outside location particulate monitors. The wind speed sensor has a range of 0 to 40 m/s and an accuracy of ±1% for wind speeds of up to 30 m/s and ±3% for wind speeds of 30 to 40 m/s. The wind direction sensor has an accuracy of ±2 degrees for wind speeds up to 30 m/s and ±5 degrees for wind speeds of 30 to 40 m/s. Traffic data were collected with a remote traffic microwave sensor G4 unit (ISS Model K4-LV-CAM). The unit is a radar sensor capable of providing per-lane presence as well as volume, occupancy, speed, and classification information.

PM concentration data were collected during the morning peak (7:00 to 9:00 a.m.) and evening peak (4:00 to 6:00 p.m.) at each shelter. Data were collected on two different days at each shelter, yielding two morning and two evening sample sets for each location. Data collection occurred primarily on Fridays between late March and mid-May, with one collection on a Tuesday at both Location 1 and Location 3. Data were not collected during one evening period at Location 1 because of poor weather conditions. Data were only partially collected for one morning period at Location 2 because of a power issue when the batteries for one device failed unexpectedly. Wind speed and direction were collected during four sampling periods: morning wind data on April 8 and April 29 and evening wind data on March 22 and May 13. Wind data were unable to be collected on other collection dates because of poor weather conditions.

RESULTS AND ANALYSIS

Data were analyzed to investigate relationships between bus shelter exposure and shelter orientation, wind speed and direction, and vehicle flow.

Orientation

Figure 2 shows morning peak UFP and $PM_{2.5}$ concentrations inside and outside the shelter at each shelter location for three dates: April 5, May 13, and April 15 for Locations 1, 2, and 3, respectively. Data are averaged to 5-min intervals. Shelters facing toward the roadway (Locations 2 and 3) display opposing trends compared with the shelter facing away from the roadway (Location 1). Particulate levels at Location 1 are generally greater outside the shelter, and spikes in concentration levels are more pronounced outside the shelter. Particulate levels at Locations 2 and 3 are generally greater inside the shelter, and spikes in concentration levels are more pronounced inside the shelter.

Notably, $PM_{2.5}$ concentrations are relatively steady at Location 2 compared with levels at other locations. In addition, the difference in mean concentration level between inside and outside is greater at Location 2 than at the other locations. Inside levels of $PM_{2.5}$ concentration average 4.75 $\mu g/m^3$ greater than outside levels compared with 2.10 $\mu g/m^3$ at Location 3 and a negligible difference at Location 1. Mean UFP concentration differences are greatest at Location 1; average outside levels are 16,190 particles/cm^3 greater than inside levels. Average UFP concentrations are higher inside the shelters at Locations 2 and 3.

One-sided paired *t*-tests were used to evaluate whether particulate levels inside the bus shelter were greater than particulate levels outside the shelter. Particulate levels were found to be significantly greater ($\alpha = 0.05$) inside the bus shelter when the shelter faced toward the roadway and significantly greater outside the bus shelter when the shelter faced away from the roadway. Results are shown in Table 2. Values in bold type indicate the higher mean concentration when inside and outside shelter data are compared.

Peaks in concentration are of special interest when damaging health effects related to short, intense bursts of exposure are considered (*6*). Chi-square tests of independence were used to evaluate whether concentration spikes were greater inside the shelter than outside the shelter. The magnitude of particulate concentration spikes was found to be statistically different ($\alpha = 0.05$) inside and outside the bus shelters for all particulate sizes with the exception of UFP.

When the shelter faced the roadway, measurements inside the shelter were, on average, 29% more than measurements outside the shelter. In contrast, when the shelter faced away from the roadway, measurements inside the shelter were 1% less than measurements outside the shelter.

Wind Speed and Direction

Figure 3 shows plots of observed concentrations of UFP and $PM_{2.5}$ varying by wind speed and direction at each shelter location; polar plots were used for three dates: April 29, May 13, and March 22 for Locations 1, 2, and 3, respectively. In these plots, the angular coordinate is given by wind direction and the radial coordinate is the wind speed. Wind speeds are denoted by concentric circles incremented to units of 0.5 m/s. At each of the coordinates in the two-dimensional plane, the third dimension is plotted on the basis of a color-scale gradient. Higher concentrations are shown as red hues on the scale gradient and indicate concentration levels most affected by wind direction. Each vertical pair of plots represents inside the shelter (top) and outside the shelter (bottom). For instance, the UFP concentrations at Location 1 are clearly highest when the wind is from the east. Shelter orientation relative to cardinal directions is given in the figure captions. The plots in Figure 3 were created by using the OpenAir package in the statistical software program R (*33*).

Figure 3 indicates that UFP concentrations are at their highest when winds are from the east (Figure 3*a,* shelter facing north) and from the southwest (Figure 3*c,* shelter facing north). $PM_{2.5}$ concentrations are highest when winds are from the north, though Figure 3*c* shows that $PM_{2.5}$ concentrations both inside and outside the shelter are unaffected by any one wind direction.

Wind direction affects particulate concentrations differently in each shelter location and for each shelter orientation. Figure 3*c* best

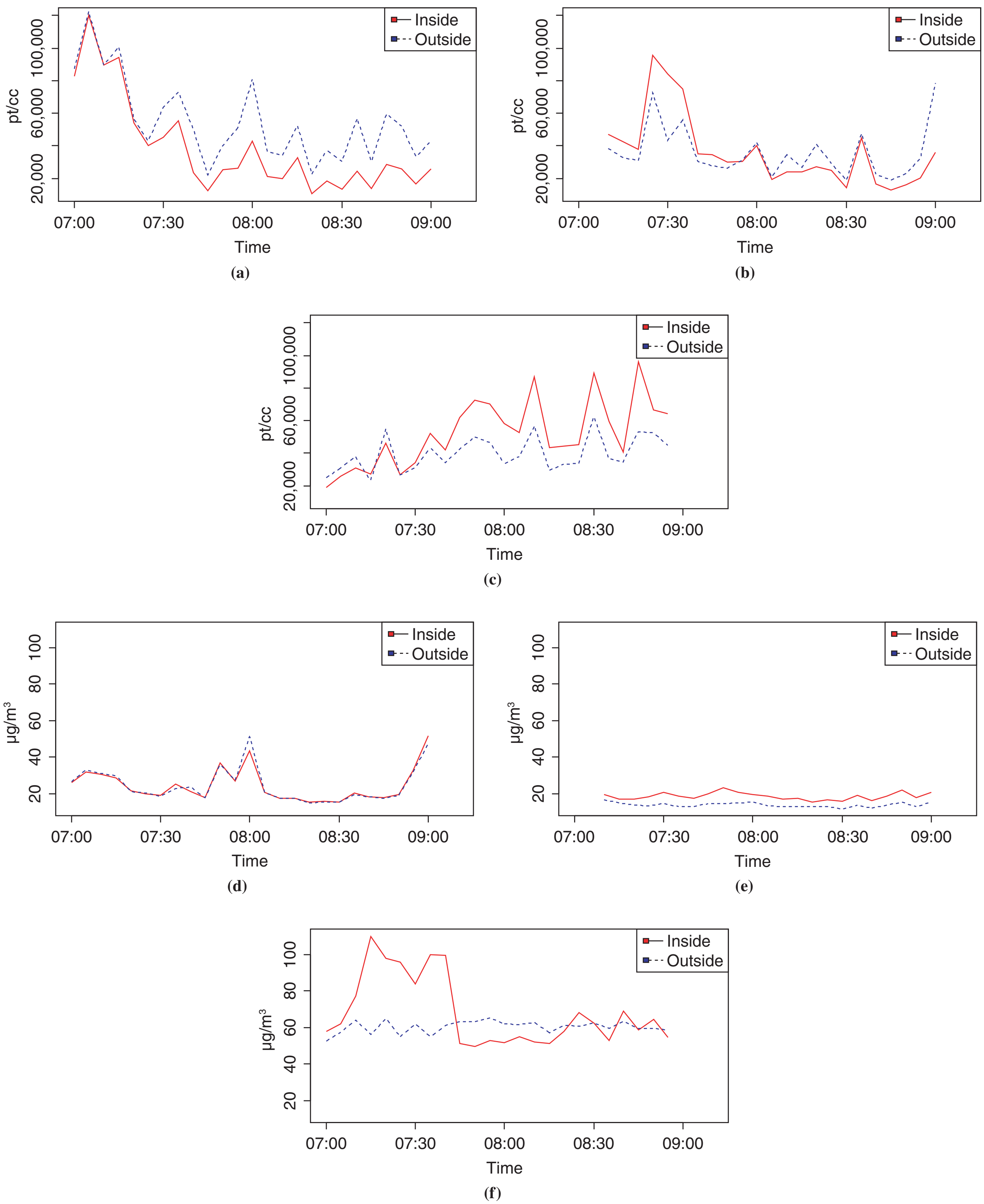

FIGURE 2 Morning concentrations inside and outside bus shelter at 5-min time intervals at each location: (*a*) UFP for April 5, Location 1, facing away from roadway; (*b*) UFP for May 13, Location 2, facing toward roadway; (*c*) UFP for April 15, Location 3, facing toward roadway; (*d*) $PM_{2.5}$ for April 5, Location 1, facing away from roadway; (*e*) $PM_{2.5}$ for May 13, Location 2, facing toward roadway; and (*f*) $PM_{2.5}$ for April 15, Location 3, facing toward roadway.

TABLE 2 Summary Statistics for Each Shelter Location

			Morning			Evening		
Date	Particulate Type	Sample Location	Mean Concentration[a]	*t*-Value	*p*-Value	Mean Concentration[a]	*t*-Value	*p*-Value
Location 1 (Away from Roadway)								
4/5/2011	UFP (pt/cc)	Inside	38,597	−37.29	<.001	—	na	na
		Outside	**54,915**					
	$PM_{1.0}$ (μg/m^3)	Inside	21.99	−1.26	.2080	—	na	na
		Outside	**22.23**					
	$PM_{2.5}$ (μg/m^3)	Inside	23.30	−1.38	.1687	—	na	na
		Outside	**23.56**					
	PM_{10} (μg/m^3)	Inside	**30.51**	24.06	<.001	—	na	na
		Outside	25.37					
4/29/2011	UFP (pt/cc)	Inside	**34,560**	−0.77	.4504	17,153	−53.75	<.001
		Outside	33,137			**21,032**		
	$PM_{1.0}$ (μg/m^3)	Inside	**20.25**	13.99	<.001	8.63	−74.34	<.001
		Outside	15.14			**11.79**		
	$PM_{2.5}$ (μg/m^3)	Inside	**20.48**	14.01	<.001	8.72	−73.71	<.001
		Outside	15.34			**11.92**		
	PM_{10} (μg/m^3)	Inside	**21.16**	11.31	<.001	10.36	−54.83	<.001
		Outside	17.31			**13.31**		
Location 2 (Toward Roadway)								
4/8/2011	UFP (pt/cc)	Inside	50,427	−18.05	<.001	11,307	−1.80	.0708
		Outside	**56,719**			**11,496**		
	$PM_{1.0}$ (μg/m^3)	Inside	59.67	na	na	**8.61**	14.47	<.001
		Outside	—			7.50		
	$PM_{2.5}$ (μg/m^3)	Inside	60.14	na	na	**8.78**	15.06	<.001
		Outside	—			7.61		
	PM_{10} (μg/m^3)	Inside	64.16	na	na	**10.60**	5.77	<.001
		Outside	—			9.98		
5/13/2011	UFP (pt/cc)	Inside	**36,020**	5.36	<.001	**14,201**	42.59	<.001
		Outside	33,680			9,248		
	$PM_{1.0}$ (μg/m^3)	Inside	**17.93**	82.86	<.001	12.46	−32.59	<.001
		Outside	13.31			**15.66**		
	$PM_{2.5}$ (μg/m^3)	Inside	**18.37**	85.00	<.001	12.71	−31.65	<.001
		Outside	13.61			**15.83**		
	PM_{10} (μg/m^3)	Inside	**21.19**	42.19	<.001	15.86	−25.06	<.001
		Outside	17.66			**19.91**		
Location 3 (Toward Roadway)								
3/22/2011	UFP (pt/cc)	Inside	**53,545**	21.77	<.001	**31,362**	21.77	<.001
		Outside	48,487			28,559		
	$PM_{1.0}$ (μg/m^3)	Inside	**23.30**	9.30	<.001	**11.27**	35.87	<.001
		Outside	21.16			9.48		
	$PM_{2.5}$ (μg/m^3)	Inside	**24.07**	9.97	<.001	**11.72**	37.91	<.001
		Outside	21.71			9.83		
	PM_{10} (μg/m^3)	Inside	**25.93**	3.79	<.001	14.13	−3.33	<.001
		Outside	25.04			**14.67**		
4/15/2011	UFP (pt/cc)	Inside	**53,790**	31.35	<.001	**56,590**	22.35	<.001
		Outside	40,457			35,994		
	$PM_{1.0}$ (μg/m^3)	Inside	**66.46**	0.00	.9987	**9.72**	12.44	<.001
		Outside	60.35			8.92		
	$PM_{2.5}$ (μg/m^3)	Inside	**68.53**	1.29	.2102	**9.89**	12.62	<.001
		Outside	60.62			9.07		
	PM_{10} (μg/m^3)	Inside	**76.23**	1.78	.0892	**10.40**	8.23	<.001
		Outside	62.40			10.09		

NOTE: pt/cc = particles per cm^3; — = missing data; na = not applicable.
[a]Bold values indicate the greater concentration (inside or outside the shelter).

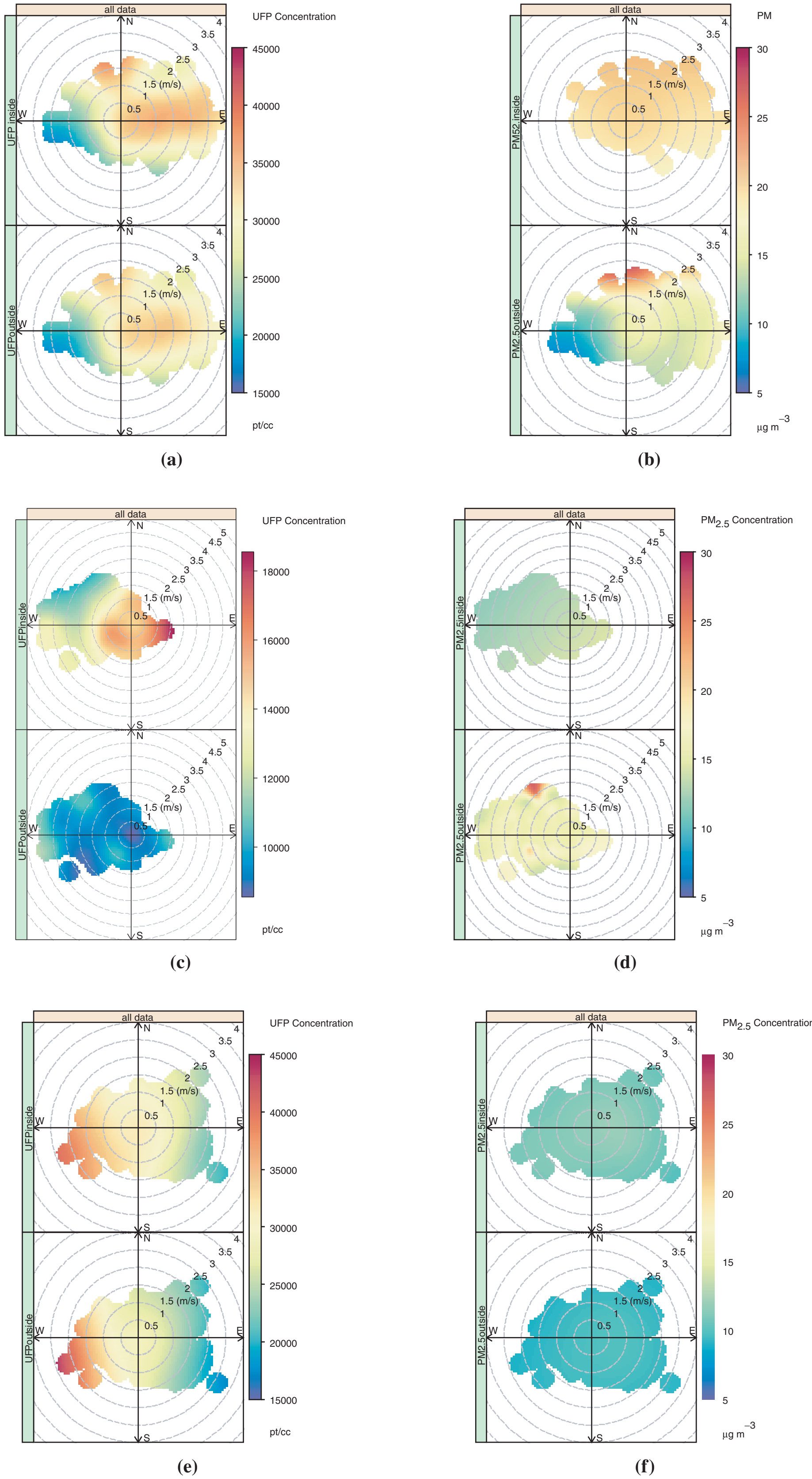

FIGURE 3 Bivariate polar plots illustrating wind speed and direction effects on UFP and $PM_{2.5}$ concentrations at each location: (*a*) morning UFP for Location 1, facing north away from roadway; (*b*) morning $PM_{2.5}$ for Location 1, facing north away from roadway; (*c*) evening UFP for Location 2, facing south toward roadway; (*c*) evening UFP for Location 3, facing south toward roadway; (*d*) evening $PM_{2.5}$ for Location 2, facing south toward roadway; (*e*) evening UFP for Location 3, facing north toward roadway; and (*f*) evening $PM_{2.5}$ for Location 3, facing north toward roadway.

illustrates discrepancies in particulate behavior: UFP concentrations inside and outside the shelter are equally affected by wind direction, as shown by the highest concentrations, which are always affected by westerly winds and increase with intensity. Conversely, $PM_{2.5}$ concentrations appear to be unaffected by wind direction outside the shelter, indicated by uniform hues in all directions, whereas concentrations inside the shelter are minimally affected by easterly wind directions at very low wind speeds, shown by slightly higher color saturations.

Increasing wind speed generally results in lower concentrations, although this result is not always the case. UFP concentrations inside the shelter in Figure 3*a* increase with wind speed, indicating potential entrapment of particles within the shelter. $PM_{2.5}$ concentrations inside the shelter at the same location are unaffected by wind speed in contrast to concentrations outside the shelter, which exhibit the expected behavior.

Vehicle Flow

Figure 4 shows vehicle flow and either morning UFP concentrations (Figure 4*a*) or evening $PM_{2.5}$ concentrations (Figure 4*b*) inside and outside bus shelter locations. Particulate concentrations are averaged to 5-min intervals. Vehicle counts were collected every 5 s and were aggregated to 5-min intervals to match particulate intervals. In several cases, upward or downward traffic trends were observed, notably during the morning sampling period at Location 3, in which traffic flow gradually rises from 7:00 to 8:00 a.m.

Morning vehicle flow averaged 1,267 vehicles per h (veh/h) at shelters located on the westbound (inbound) direction of travel. Evening vehicle flow averaged 1,415 veh/h. At Location 3 (the only shelter on the eastbound direction of travel), morning and evening vehicle flow averaged 1,042 and 1,356 veh/h, respectively. Overall, heavy vehicles (length greater than 6 m) made up roughly 8% of traffic.

An analysis of variance was performed to test for positive relationships between dependent variables (particulate concentrations) and independent variables (vehicle flow, wind speed, and wind direction). A sample UFP ANOVA is shown in Table 3 for dates when wind data were available. The statistical significance of the variables is indicated by the number of asterisks, with associated *p*-values given in a footnote to the table.

Vehicle flow exhibits a significant positive relationship on UFP concentrations inside the bus shelter at Locations 1 and 3 ($\alpha = 0.01$). $PM_{1.0}$ concentrations were significant inside the bus shelter at Locations 2 and 3 ($\alpha = 0.05$). $PM_{2.5}$ concentrations were significant inside the bus shelter at Locations 2 and 3 ($\alpha = 0.05$). PM_{10} concentrations were significant inside the bus shelter at Location 3 ($\alpha = 0.01$). UFP concentrations outside the bus shelter at Location 1 were the only concentration significant outside the bus shelter ($\alpha = 0.05$).

DISCUSSION OF RESULTS

The results of this analysis suggest that shelter orientation, wind speed and direction, and vehicle flow play some role in particulate concentration levels surrounding a bus stop shelter. Particulate concentrations were significantly greater inside than outside at shelters facing toward the roadway. In contrast, particulate concentrations were significantly greater outside the shelter than inside for those facing away from the roadway. Orienting a shelter away from the roadway has the potential to shield bus patrons from PM compared with a shelter facing toward the roadway.

Orientation is an issue because of the three-panel shape of the shelter, which encloses a volume of air subject to different interactions with vehicle emissions than the open roadway environment. When the shelter faces the roadway, this enclosed volume of air may be described as a trap for particulates, suspending the matter in an enclosed area where dispersion does not immediately take place. Allowing for increased airflow through a shelter that faces the roadway could increase circulation and speed dispersal of particulates. Particulates from the roadway are not immediately introduced into a shelter facing away from the roadway, allowing time for dispersion. Chi-square tests indicate that a buffer effect is present for spikes in $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, but not for UFP. Shelters situated in close proximity to the roadway, as at Location 1, would be exposed to the highest particulate concentrations, which have not yet dispersed over greater distances.

Vehicle flow was found to significantly influence all particulate levels inside the bus shelters and, to a limited degree, outside the bus shelter. The environment inside the shelter is likely much more affected by vehicle presence because of a slower exchange of air. Vehicle-borne particulates are trapped in the shelter, whereas outside the shelter they disperse much more quickly. No particulate size was more significant than the rest, suggesting similar interactions between vehicle flow and all particulate sizes. Further investigation will need to consider vehicle classification as a variable, which may help to explain spikes in concentration such as the $PM_{2.5}$ spikes at Location 3 (Figure 4*b*).

The study has a number of limitations. The side walls of the shelter may play a role in shielding efficiency of a shelter that faces away from the roadway. The shelter facing away from the roadway in this study had shorter walls (~0.6 m long) than the shelters facing the roadway (~1.2 m long). It is possible that the volume of air contained in the shelter, which is less than that in a shelter with longer walls, could affect particulate concentration levels. This relationship would need to be investigated in a future study because no shelters with longer sidewalls facing away from the roadway exist along the studied corridor.

Shelters placed on the nearside of an intersection (Locations 1 and 2) were not observed to have consistently higher particulate concentrations than farside shelters, despite vehicles idling within several meters of the shelters during red signals. Intersection location was not the primary focus of this study and will need to be investigated further as a variable in future studies.

Particulate concentrations inside and outside shelters were primarily affected by east–west winds, predictable in Portland, where the prevailing winds are from the east out of the Columbia Gorge during the fall and winter months (from about October to March) and from the west off the Pacific Ocean during the spring and summer months (April to September). Increased wind speed generally resulted in lower concentration levels because of increased dilution through turbulence and advection. The shelters are oriented parallel to the prevailing wind; that is, their primary axes are in line with the wind. Studying shelters perpendicular to the prevailing wind, such that the wind blows into the shelter opening or against its back panel, may reveal different interactions between particulate concentrations and wind speed or direction. No such shelter orientations were available along the studied corridor.

This study focuses on a few aspects of particulate concentrations in a complicated environment that includes wind variation, changing traffic patterns, and routine presence of large diesel vehicles (such as buses). Although orientation, wind speed and direction, and vehicle flow appear to have an impact on exposure levels, future

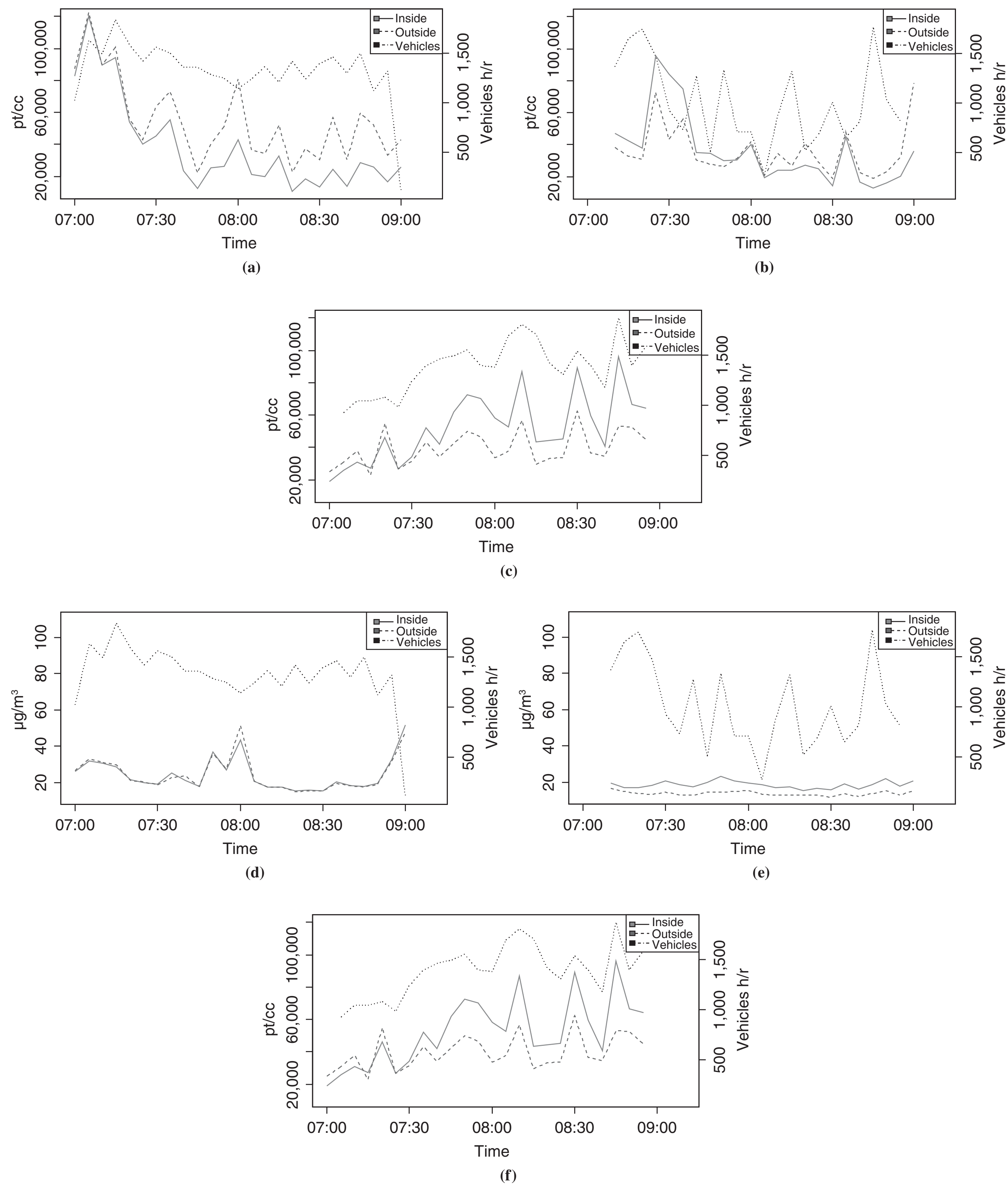

FIGURE 4 Morning concentrations at each bus shelter location inside and outside, overlaid with hourly vehicle flow per 5-min time intervals: (*a*) vehicles and UFP for April 5, Location 1, facing away from roadway; (*b*) vehicles and UFP for May 13, Location 2, facing toward roadway; (*c*) vehicles and UFP for April 15, Location 3, facing toward roadway; (*d*) vehicles and $PM_{2.5}$ for April 5, Location 1, facing away from roadway; (*e*) vehicles and $PM_{2.5}$ for May 13, Location 2, facing toward roadway; and (*f*) vehicles and $PM_{2.5}$ for April 15, Location 3, facing toward roadway.

TABLE 3 Sample ANOVA for UFP Inside and Outside Shelter

	UFP Inside				UFP Outside			
	Df	SS	*F*-Ratio	Sig.	Df	SS	*F*-Ratio	Sig.
Evening, Location 3 (Shelter Facing Toward Roadway)—March 22								
Vehicles	1	381.00	0	††	1	474.71 E04	0.0273	††
Wind speed	1	169.48 E07	8.3691	**	1	720.30 E36	414.12	*
Wind direction	1	432.61 E04	0.0214	††	1	294.05 E06	1.6906	††
Morning, Location 2 (Shelter Facing Toward Roadway)—April 8								
Vehicles	1	343.23 E07	6.7763	**	1	275.36 E07	6.7448	**
Wind speed	1	653.82 E07	12.9082	***	1	550.18 E07	13.4766	***
Wind direction	1	414.00 E08	81.7345	***	1	208.05 E08	50.9607	***
Morning, Location 1 (Shelter Facing Away from Roadway)—April 29								
Vehicles	1	105.31 E07	3.6425	†	1	115.80 E07	4.0312	*
Wind speed	1	904.63 E06	3.1288	†	1	856.45 E06	1.9816	†
Wind direction	1	985.35 E07	34.0803	***	1	689.47 E07	24.0026	***
Evening, Location 2 (Shelter Facing Toward Roadway)—May 13								
Vehicles	1	388.34 E05	1.2530	††	1	658.97 E03	0.2040	††
Wind speed	1	141.71 E07	45.7243	***	1	405.55 E05	12.5549	***
Wind direction	1	168.18 E06	5.4267	*	1	774.12 E04	2.3965	††

NOTE: Df = degrees of freedom; SS = sum of squares; sig. = significance.
††$p < 1$; †$p < .1$; *$p < .05$; **$p < .01$; ***$p < .001$.

studies will need to consider other variables to effectively control for as many factors as possible when the significance of varying particulate levels is determined. This study has effectively controlled for the surrounding environment (including meteorological variables and point pollution sources such as gas stations) at each location by measuring particulate levels inside and outside bus stop shelters simultaneously. Many more factors need to be isolated and analyzed to determine their relationship with particulate levels, including percentage of heavy vehicles on the roadway, nearside versus farside shelter location, and distance of shelter to the curb. Air quality data will need to be synchronized with those missing factors to determine most accurately the relationships between particulate levels, traffic, and the surrounding built environment.

CONCLUSION

PM, as a common air pollutant recognized by the NAAQS, is a key contributor to urban air quality concerns. This study uses a comparative approach to determine PM concentrations inside and outside bus shelters along a busy urban corridor, with particular attention paid to the orientation of the bus stop shelter. To the best of the authors' knowledge, this is the first study that analyzes the impact of shelter orientation on transit users' exposure at bus stops. Bus stop orientation is shown to play a statistically significant role in PM levels and, consequently, exposure.

Currently, guidelines for the location and design of bus stops do not take into account air quality or exposure considerations. The results of this research strongly suggest that it is possible to reduce exposure by changing the orientation of a bus shelter. Additional research is needed to expand the number of case studies and better understand the impact of traffic levels, bus shelter orientation, and exposure levels as well as to warrant a stronger recommendation in bus shelter location and design guidelines.

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REFERENCES

1. Pisarski, A. E. *NCHRP Report 550/TCRP Report 110: Commuting in America III: The Third National Report on Commuting Patterns and Trends.* Transportation Research Board of the National Academies, Washington, D.C., 2006.
2. *National Ambient Air Quality Standards (NAAQS).* U.S. Environmental Protection Agency, 1990. http://www.epa.gov/air/criteria.html.
3. Morawska, L., M. R. Moore, and Z. D. Ristovski. *Health Impacts of Ultrafine Particles: Desktop Literature Review and Analysis.* Australian Department of the Environment and Heritage, Canberra, 2004.
4. Ballester, F., S. Medina, E. Boldo, P. Goodman, M. Neuberger, C. Iñiguez, and N. Künzli. Reducing Ambient Levels of Fine Particulates Could Substantially Improve Health: A Mortality Impact Assessment for 26 European Cities. *Journal of Epidemiology and Community Health,* Vol. 62, No. 2, Feb. 2008, pp. 98–105.
5. Bedada, G. B., J. Heinrich, T. Götschi, S. H. Downs, B. Forsberg, D. Jarvis, C. Lucznska, A. Soon, J. Sunyer, and N. Künzli. Urban Background Particulate Matter and Allergic Sensitization in Adults of ECRHS II. *International Journal of Hygiene and Environmental Health,* Vol. 210, No. 6, 2007, pp. 691–700.
6. Michaels, R. A., and M. T. Kleinman. Incidence and Apparent Health Significance of Brief Airborne Particle Excursions. *Aerosol Science and Technology,* Vol. 32, No. 2, 2000, pp. 93–105.

7. Møller, P., J. K. Folkman, L. Forchhammer, E. V. Bräuner, P. H. Danielsen, L. Risom, and S. Loft. Air Pollution, Oxidative Damage to DNA, and Carcinogenesis. *Cancer Letters,* Vol. 266, No. 1, 2008, pp. 84–97.
8. Vinzents, P. S., P. Møller, M. Sørensen, L. E. Knudsen, O. Hertel, F. P. Jensen, B. Schibye, and S. Loft. Personal Exposure to Ultrafine Particles and Oxidative DNA Damage. *Environmental Health Perspectives,* Vol. 113, No. 11, 2005, pp. 1485–1490.
9. Pope, C. A. III, R. T. Burnett, G. D. Thurston, M. J. Thun, E. E. Calle, D. Krewski, and J. J. Godleski. Cardiovascular Mortality and Long-Term Exposure to Particulate Air Pollution. *Circulation,* Vol. 109, No. 1, 2004, pp. 71–77.
10. Vallero, D. A. *Fundamentals of Air Pollution.* Academic Press, New York, 2008.
11. Chuang, K. J., C. C. Chan, T. C. Su, C. T. Lee, and C. S. Tang. The Effect of Urban Air Pollution on Inflammation, Oxidative Stress, Coagulation, and Autonomic Dysfunction in Young Adults. *American Journal of Respiratory and Critical Care Medicine,* Vol. 176, No. 4, 2007, p. 370.
12. Samet, J. M., F. Dominici, F. C. Curriero, I. Coursac, and S. L. Zeger. Fine Particulate Air Pollution and Mortality in 20 US Cities, 1987–1994. *New England Journal of Medicine,* Vol. 343, No. 24, 2000, p. 1742.
13. Chuang, K. J., C. C. Chan, N. T. Chen, T. C. Su, and L. Y. Lin. Effects of Particle Size Fractions on Reducing Heart Rate Variability in Cardiac and Hypertensive Patients. *Environmental Health Perspectives,* Vol. 113, No. 12, 2005, p. 1693.
14. Kaur, S., M. J. Nieuwenhuijsen, and R. N. Colvile. Fine Particulate Matter and Carbon Monoxide Exposure Concentrations in Urban Street Transport Microenvironments. *Atmospheric Environment,* Vol. 41, No. 23, 2007, pp. 4781–4810.
15. Gulliver, J., and D. J. Briggs. Personal Exposure to Particulate Air Pollution in Transport Microenvironments. *Atmospheric Environment,* Vol. 38, No. 1, 2004, pp. 1–8.
16. Kittelson, D. B. Engines and Nanoparticles: A Review. *Journal of Aerosol Science,* Vol. 29, No. 5–6, 1998, pp. 575–588.
17. Hitchins, J., L. Morawska, R. Wolff, and D. Gilbert. Concentrations of Submicrometre Particles from Vehicle Emissions near a Major Road. *Atmospheric Environment,* Vol. 34, No. 1, Jan. 2000, pp. 51–59.
18. Wayne, W. S., N. N. Clark, R. D. Nine, and D. Elefante. A Comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses. *Energy Fuels,* Vol. 18, No. 1, 2004, pp. 257–270.
19. Adams, H. S., M. J. Nieuwenhuijsen, and R. N. Colvile. Determinants of Fine Particle (PM2. 5) Personal Exposure Levels in Transport Microenvironments, London, UK. *Atmospheric Environment,* Vol. 35, No. 27, 2001, pp. 4557–4566.
20. Zhu, Y., W. C. Hinds, S. Kim, S. Shen, and C. Sioutas. Study of Ultrafine Particles near a Major Highway with Heavy-Duty Diesel Traffic. *Atmospheric Environment,* Vol. 36, No. 27, 2002, pp. 4323–4335.
21. Kendrick, C. M., A. Moore, A. Haire, A. Bigazzi, M. Figliozzi, C. M. Monsere, and L. George. Impact of Bicycle Lane Characteristics on Exposure of Bicyclists to Traffic-Related Particulate Matter. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2247,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 24–32.
22. Briggs, D. J., K. de Hoogh, C. Morris, and J. Gulliver. Effects of Travel Mode on Exposures to Particulate Air Pollution. *Environment International,* Vol. 34, No. 1, 2008, pp. 12–22.
23. Kaur, S. *Exposure Assessment of Urban Street Users to Particulate Matter and Carbon Monoxide.* PhD thesis. Imperial College London, University of London, United Kingdom, 2006.
24. Chan, L. Y., W. L. Lau, S. C. Lee, and C. Y. Chan. Commuter Exposure to Particulate Matter in Public Transportation Modes in Hong Kong. *Atmospheric Environment,* Vol. 36, No. 21, 2002, pp. 3363–3373.
25. Jackson, E. D., and B. A. Holmén. Modal Analysis of Vehicle Operation and Particulate Emissions from Connecticut Transit Buses. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2123,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 76–87.
26. Holmén, B. A., and A. Ayala. Ultrafine PM Emissions from Natural Gas, Oxidation-Catalyst Diesel, and Particle-Trap Diesel Heavy-Duty Transit Buses. *Environmental Science and Technology,* Vol. 36, No. 23, 2002, pp. 5041–5050.
27. Schimek, P. Reducing Emissions from Transit Buses. *Regional Science and Urban Economics,* Vol. 31, No. 4, July 2001, pp. 433–451.
28. Adams, H. S., M. J. Nieuwenhuijsen, R. N. Colvile, M. A. S. McMullen, and P. Khandelwal. Fine Particle (PM2.5) Personal Exposure Levels in Transport Microenvironments, London, UK. *Science of the Total Environment,* Vol. 279, Nos. 1–3, Nov. 2001, pp. 29–44.
29. Zhu, S., P. Demokritou, and J. Spengler. Experimental and Numerical Investigation of Micro-environmental Conditions in Public Transportation Buses. *Building and Environment,* Vol. 45, No. 10, 2010, pp. 2077–2088.
30. Fitzpatrick, K., K. Hall, D. Perkinson, and L. Nowlin. *TCRP Report 19: Guidelines for the Location and Design of Bus Stops.* TRB, National Research Council, Washington, D.C., 1996.
31. Hess, D. B., P. D. Ray, A. E. Stinson, and J. Y. Park. Determinants of Exposure to Fine Particulate Matter (PM2. 5) for Waiting Passengers at Bus Stops. *Atmospheric Environment,* Vol. 44, 2010, pp. 5174–5182.
32. Kaur, S., M. J. Nieuwenhuijsen, and R. N. Colvile. Pedestrian Exposure to Air Pollution Along a Major Road in Central London, UK. *Atmospheric Environment,* Vol. 39, No. 38, 2005, pp. 7307–7320.
33. Carslaw, D. C., and K. Ropkins. *Open-Source Tools for Analysing Air Pollution Data.* Environmental Research Group, King's College, London, United Kingdom, Apr. 2011.

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