An Empirical Study of Particulate Matter Exposure for Passengers Waiting at Bus Stop Shelters in Portland, Oregon, USA

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Abstract

Current guidelines for the location and design of bus stops do not take into account air quality or exposure considerations for waiting passengers. This paper compares the exposure of transit riders waiting at three-sided bus stop shelters that either: 1) face roadway traffic, or 2) face away from roadway traffic. Shelters were instrumented with devices to monitor particulate matter concentration inside and outside the shelter, wind speed and direction, and vehicle counts. Data were collected at three shelters during both the morning and afternoon peak periods. Bus shelter orientation is found to have a significant effect on the concentration of four sizes of particulate matter: ultrafine particles, PM_1, $PM_{2.5}$, and PM_{10}. It was observed that shelters with an opening oriented towards the roadway had consistently 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. Particulate concentrations are shown to vary based on both wind speed and direction. Qualitative analysis conducted on select variables suggests temperature and humidity are the dominant influencers of concentrations across all four particulate sizes. Vehicle flows can have significant correlations with ultrafine particulate counts, though not consistently.

Introduction

This paper utilizes original data, including air quality samples, wind speed and direction, and traffic counts, to assess environmental impacts on the concentration of particulate matter air pollution inside and outside semi-enclosed bus stop shelters in Portland, Oregon, USA. Such shelters are common in urban areas and have traditionally been placed on high-ridership routes as a convenience to waiting passengers. Little research has been conducted to determine whether orientation of bus shelters relative to the roadway significantly affects exposure to roadside air pollution, and no published study has examined the variables considered in this paper simultaneously.

Environmental concerns constitute a rising trend among the general public, demanding focused research to best understand the impact we have on our surroundings. It is important to understand impacts to human health in the built environment of some of our most populated (and polluted0 urban areas to mitigate risks and raise quality of life. Arterial corridors are vital components of the urban fabric, traveled by thousands daily using a variety of modes. Commuters choose public transportation for a number of reasons, one of which may be to reduce their impact on the environment. Ironically, those waiting at bus stops may be in a microenvironment with substandard air quality, exposed to elevated levels of air pollution.

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, as a result of waiting for buses near busy corridors. However, transit user exposure at bus stops has not been properly addressed in the extant literature.

Background and Literature Review

Particulate matter (PM) is one of six common air pollutants regulated by the National Ambient Air Quality Standards (NAAQS), established by the US Environmental Protection Agency (EPA) as part of the Clean Air Act (EPA 1990). PM is a complex mixture of solid and liquid material, made up of carbon particles, hydrocarbons and inorganics. PM is unsafe at any exposure level, meaning human health is jeopardized at any exposure level (Morawska et al. 2004). Despite being relatively nonreactive, PM is highly variable in composition and often contains chemically reactive substances on the particle surface (Vallero 2008).

PM is generally classified into four categories based on 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 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, or pt/cc) as opposed to particle mass (mg/m^3 or µg/m^3)for $PM_{1.0}$ and larger.

Ambient urban PM_{10} background concentrations, unaffected by roadway sources, range from 17-61 µg/m^3 (Ballester et al. 2008). Ambient urban $PM_{2.5}$ background concentrations are generally below 16 µg/m^3 (Bedada et al. 2007). Ambient urban UFP background concentrations range from a few thousand to 20 thousand particles/cm^3 (Morawska et al. 2004). NAAQS exposure standards were most recently revised in 2006 to tighten the 24-hour $PM_{2.5}$ standard to 35 µg/m^3, while the 24-hour 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 the EPA. While the EPA bases its air quality standards on annual and 24-hour exposures, it is thought that peak exposures (one hour or less in duration) are most relevant to human health and exacerbation of existing symptoms (Michaels and Kleinman 2000).

Much attention has been given to the epidemiological association between exposure to PM and adverse health outcomes (Møller et al. 2008; Vinzents et al. 2005; Morawska et al. 2004; Pope III et al. 2004). Also referred to as soot, black carbon, black smoke and fine particle pollution, PM exhibits gas-like 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 due to the small size of the particles (Vallero 2008). PM has been linked to aggravation of asthma, chronic bronchitis and decreased lung function (Vallero 2008). Many studies have documented negative cardiovascular effects from exposure to PM_{10} and $PM_{2.5}$ (Chuang et al. 2007; Samet et al. 2000), while $PM_{1.0}$ and UFP have been shown to increase cardiorespiratory symptoms for elderly patients (Chuang et al. 2005).

Individuals traveling within transport microenvironments may be exposed to higher levels of pollution, comprising a significant percentage of their daily total exposure within a short amount of time (Kaur et al. 2007; Gulliver and Briggs 2004). Elevated concentrations of particulate matter near roads in excess of ambient urban concentrations indicate a direct relationship to vehicle emissions (Kittelson 1998). Those waiting for buses are often waiting along busy corridors at peak hours, increasing the likelihood of elevated exposure. "Hot spots" of PM concentration can occur near multilane intersections in urban environments (Vallero 2008), and buildings can restrict air movement and limit the volume of air in which the pollution is contained, exacerbating the problem (Vardoulakis et al. 2003). Lung et al. (2005) found $PM_{2.5}$ concentrations to be nearly double at intersections located near buildings versus intersections in open space. Bus stops are likely to be placed at intersections to allow patrons ease of access to transfer points.

Motor vehicles are the primary source of fine and ultrafine particles along transportation corridors (Hitchins et al. 2000). The majority of particle numbers are in the 0.02-0.13 µm range for diesel engines (Morawska et al. 1998) and 0.02-0.06 µm for gasoline engines (Ristovski et al. 1998). Diesel vehicles are one of the largest sources of PM (EPA 1990). Diesel engines are regulated by fuel flow only, differing from gasoline engines in that air flow remains constant with engine speed. 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 (Vallero 2008; Wayne et al. 2004; Kittelson 1998). PM emissions from diesel engines are regulated by the EPA, most recently set at a maximum of 0.01 g/bhp-hr (EPA 2007). Although recent EPA standards have targeted diesel engines and mandated more stringent PM emission standards, existing diesel vehicles are likely to remain in operation for some years to come due to the longevity and durability of diesel engines.

Exposure to pollutants in transportation microenvironments is often more complex than ambient conditions from a fixed monitoring station may describe (Adams et al.2001a). 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 micro-scale impacts, and as a result may not adequately describe small-scale conditions in close proximity to traffic (Gulliver and Briggs 2004; Adams et al. 2001a). Gulliver and Briggs (2004) found a fixed monitoring station to be a poor marker for PM_{10} concentrations one kilometer away from their sampling location. UFP concentrations in particular decrease significantly with distance due to dispersion and coagulation into larger particles, returning to background levels around 300 meters downwind from the roadway (Zhu et al. 2002). A fixed monitoring station would be expected to underestimate UFP concentration levels for a roadway located outside this range. Micro-scale exposure measurements resolve coagulation problems and present a more accurate picture of roadway air quality conditions (Kaur et al.2007).

Several studies have used micro-scale 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 (Briggs et al. 2008; Kaur, Nieuwenhuijsen, and Colvile 2007; Kaur 2006; L. Y. Chan et al. 2002). Public transportation exposure studies commonly focus on diesel buses, the most common vehicle in most transit agencies. Buses have repeatedly been singled out as significant sources of PM in urban areas (Jackson and Holmén 2009; Kaur, Nieuwenhuijsen, and Colvile 2007; Holmén and Ayala 2002; Schimek 2001). A common study design involving diesel buses focuses on in-vehicle bus driver and bus patron exposure. In their multi-modal study, Adams et al. (2001) observed consistent mean in-cabin $PM_{2.5}$ concentrations in the summer (39 $\mu g/m^3$) and the winter (38.9 $\mu g/m^3$). Zhu et al. (2010) examined the micro-environmental conditions in Harvard University shuttle system buses in Cambridge, MA. Concentration levels of PM_{10} ranged from 11-18 $\mu g/m^3$, depending on the sample date. Likewise, concentration levels of $PM_{2.5}$ and UFP ranged from 11-15 $\mu g/m^3$ and 40,000-57,000 pt/cc, respectively. Zhu et al. (2010) note that $PM_{2.5}$concentrations were an order of magnitude higher during peak hours, attributed by the authors to high traffic conditions.

Most reviewed air quality study designs, particularly transit-oriented studies, fail to capture the exposure for a transit patron waiting at a bus stop. Yet, bus stop location is considered to be one of the most important aspects to transit route design, determining transit system performance, traffic flow, safety, and security (Fitzpatrick et al. 1996). Bus stops are located in one of three configurations, each relative to the closest intersection: near-side, far-side, and mid-block. Near-side bus stops are located immediately before an intersection in the direction of travel. Far-side bus stops are located immediately after an intersection in the direction of travel. Mid-block 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. Bus stops are placed to give direct access to transit from the intersection or nearby land use (Fitzpatrick et al. 1996).

Shelters are often installed at a stop on the basis of meeting an established minimum threshold of boardings. Three principal factors affect placement of shelters at bus stops: 1) number of boardings and alightings, 2) major origins and destinations, and 3) major transfer points (Law and Taylor 2001). Prevailing practice suggests a minimum threshold of 50 to 100 daily boardings to justify the installation of a bus stop shelter in urban environments (Fitzpatrick et al. 1996). Shelters, then, denote bus stops where high volumes of passengers are waiting in close proximity to traffic.

Only one identified study has evaluated air quality specifically at and within bus stop shelters. Hess et al. (2010) evaluated commuter exposure to $PM_{2.5}$ for passengers waiting at seven bus stop shelters in Buffalo, NY, 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. 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 percent 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. (2010) observed morning levels that are higher than evening levels but do not note if this may be due to directional flow of commuter traffic. Longer sample durations could provide insights into morning/evening peak hour fluctuations. Only one type of shelter design is studied: shelters that face towards the roadway. This literature review was unable to find a published study that has examined differences in shelter orientation with a focus on air quality concerns.

Experimental Design and Data Collection

Bus shelters selected for monitoring are located along Powell Boulevard, a major east-west arterial located approximately two miles southeast of the central business district (CBD) of Portland, OR. 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.

There are 31 bus stops along the two-mile stretch of roadway selected for analysis. Of these 31 stops, 17 feature shelters. Location of the shelter is determined by its placement relative to the intersection. Near-side shelters are located upstream from the intersection. Far-side shelters are located downstream from the intersection. Mid-block shelters are located between two intersections. Shelters are primarily placed near-side and far-side, with only two placed in mid-block locations.

The shelters are of four different configurations, determined by panel layout and referenced in Table I as Shelter A, B, C, or D. Panels that form an opening facing the roadway are described as oriented towards 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.

This study focuses on three shelters on Powell Boulevard. Shelters were chosen primarily for their orientation. The shelter at Location 1 is oriented away from the roadway while the shelters at Locations 2 and 3 are oriented towards the roadway. Shelters facing the roadway were chosen due to their prevalence along the corridor, and Shelter A was chosen over Shelter B for its use as the primary shelter layout. Shelter C was chosen for its unique orientation away from the roadway, despite being shallower in depth than Shelter A.

The chosen shelters have similar surrounding built environments, taking into consideration similar building heights behind the shelters to control for wind characteristic effects. Table II summarizes characteristics of the shelters and the roadway. Fig. I shows the built environment surrounding the shelters.

Table I Bus Stop Shelter Characteristics along Powell Boulevard

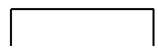
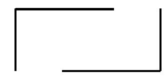
Shelter Layout		A	B	C	D	E
Number of Panels		3	3	3	4	No Shelter
Depth		4’3”	2’3”	2’3”	4’3”	-
Orientation to Roadway		Toward	Toward	Away	Both	-
Layout						-
Location	Near-side	4	1	1	1	0
	Far-side	6	1	1	0	2
	Mid-block	2	0	0	0	12
Total		12	2	2	1	14

Table II Detailed Roadside Environment Characteristics of Study Locations

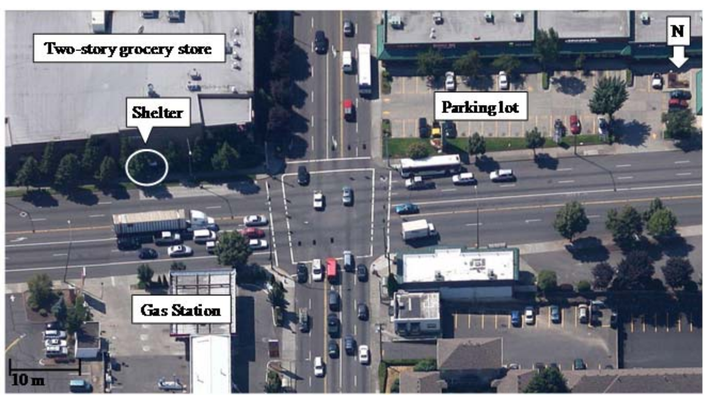
Shelter Characteristics	Location 1 (facing away from roadway)	Location 2 (facing toward roadway)	Location 3 (facing towards roadway)
Shelter Type	C	A	A
Near-side/Far-side	Near-side	Near-side	Far-side
Eastbound/Westbound on Powell	Westbound (Inbound)	Westbound (Inbound)	Eastbound (Outbound)
Distance to Curb	2’0”	9’0”	12’6”
Distance to Intersection	24’0”	12’0”	70’0”
Built Environment Behind Shelter	Multi-story building, 12’0” behind shelter	Multi-story building, 20’0” behind shelter	Multi-story building, 3’6” behind shelter
Annual Average Daily Traffic (2009)*	35,300	31,500	34,100
Percent Trucks, Morning[ǂ]	12.4%	18.6%	4.5%
Percent Trucks, Evening[ǂ]	9.7%	17.1%	5.5%
Approximate Morning Bus Headway	8 minutes	8 minutes	20 minutes
Approximate Evening Bus Headway	15 minutes	15 minutes	7 minutes
Average Boardings, Morning	1.2	1.0	1.9
Average Boardings, Evening	1.6	1.9	2.8

*http://www.oregon.gov/ODOT/TD/TDATA/tsm/docs/2009_TVT.pdf

[ǂ] Vehicle length > 20 feet

(a)

(b)



(c)

Fig. I Built environment characteristics for (a) Location 1, (b) Location 2, and (c) Location 3. Aerial photography courtesy Google.com

Particulate matter concentrations were monitored both inside and outside the shelter simultaneously to control for any changes in environmental conditions. $PM_{1.0}$–PM_{10} measurements were made using 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 prior to each use. UFP measurements were made using two P-Trak Ultrafine Particle Counters (TSI Model 8525), capable of measuring concentrations between zero and 5×10^5 particles/cm^3 and particle sizes between 0.02 and one micrometer in diameter. The DustTraks and P-Traks were started simultaneously and operated continuously at one-second resolutions for the entirety of the 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= 0.996).

Device intake points were set at five feet above the ground, following standard practice observed in similar studies (Hess et al. 2010; Kaur, Nieuwenhuijsen, and Colvile 2005; Gulliver and Briggs 2004; Adams et al. 2001). Inside the shelter, intake points were placed in the center of the shelter, approximately six inches from the rear panel (referenced as “inside location”). Outside the shelter, intake points were placed three feet from the shelter, mimicking the distance set by Hess et al. (2010), at the same distance from the curb as the monitors inside the shelter (referenced as “outside location”). 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 micro-measurements of air quality. To control for these effects, wind speed and direction were measured using an RM Young Ultrasonic Anemometer (Young Model 81000), placed next to the outside location particulate monitors. The wind speed sensor has a range of 0-40 m/s, and an accuracy of ±1% for wind speeds up to 30 m/s and ±3% for wind speeds 30-40 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 30-40 m/s. Traffic data was collected using an RTMS G4 unit (ISS Model K4-LV-CAM). The RTMS (Remote Traffic Microwave Sensor) unit is a radar sensor capable of providing per-lane presence as well as volume, occupancy, speed and classification information.

Particulate matter concentration data were collected during morning peak (7:00 am – 9:00 am) and evening peak (4:00 pm – 6:00 pm) periods 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 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 due to poor weather conditions. Data were only partially collected for one morning period at Location 2 due to 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, evening wind data on March 22 and May 13. Wind data were unable to be collected on other collection dates due to poor weather conditions. Collections were rotated between shelters so as to best account for gradual changes in meteorological conditions as winter progressed to spring. Table III details data collected on each date and at each location.

Data were not collected during one evening period at Location 1 due to poor weather conditions. Data were only partially collected for one morning period at Location 2 due to 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, evening wind data on March 22 and May 13. Wind data were unable to be collected on other collection dates due to poor weather conditions.

Table III Data Collected by Date

		Location 1		Location 2		Location 3	
		April 5	April 29	April 8	May 13	March 22	April 15
Morning	UFP						
	PM_1-PM_{10}						
	Wind						
	Traffic						
Evening	UFP						
	PM_1-PM_{10}						
	Wind						
	Traffic						

Data Collected | Outside Shelter Data Not Collected | Data Not Collected

Results and Analysis

Data were organized into dependent and independent categories. Independent variables were further organized into orientation, location, vehicle flow, and weather categories. Table IV defines variables used for analysis.

Table IV Variable Definitions

Variables	Definition	Unit
DEPENDENT VARIABLES		
UFP	Continuous variable describing concentration in 1-min average interval	pt/cc
$PM_{1.0}$	Continuous variable describing concentration in 1-min average interval	μg/m^3
$PM_{2.5}$	Continuous variable describing concentration in 1-min average interval	μg/m^3
PM_{10}	Continuous variable describing concentration in 1-min average interval	μg/m^3
INDEPENDENT VARIABLES		
Orientation		
Orientation	Dichotomous variable describing orientation of shelter, =0 if towards roadway; =1 if away from road	0,1
Location		
Inside or Outside	Dichotomous variable describing monitoring location, =0 if inside shelter; =1 if outside shelter	0,1
Intersection	Dichotomous variable describing shelter location relative to intersection, =0 if near side; =1 if far side	0,1
Traffic		
Vehicle Flow	Continuous variable describing number of vehicles present during 1-min intervals	veh/hour
Heavy Vehicle (Truck) Flow	Continuous variable describing number of heavy vehicles (length > 6 m) present during 1-min intervals	veh/hour
Weather		
Weather		
Wind Speed	Continuous variable describing wind speed in 1-min intervals	m/s
Wind Direction	Categorical variable describing direction wind is blowing from, =1 if north; =2 if northeast; =3 if east; =4 if southeast; =5 if south; =6 if southwest; =7 if west; =8 if northwest	1-8
Temperature	Continuous variable describing temperature	°C
Relative Humidity	Continuous variable describing relative humidity	%

The mean UFP concentration was 35,086 pt/cc for all data collected. The mean values of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were 21.47, 21.97, and 25.00 µg/m^3, respectively. These values are in line with existing literature for near-road conditions. Table V details summary statistics for particulates, traffic, and weather variables.

Independent variables investigated include monitoring location (inside or outside shelter), shelter orientation, diurnal patterns, wind speed, wind direction, vehicle flow, and heavy vehicle flow. Vehicle flow averaged 1,290 vehicles per hour. Note that this unit of measure is *not* vehicles per hour per lane. Rather, this is an average of all lanes of travel in the direction closest to the shelter, either two or three lanes depending on the location.

Wind speed averaged less than 1 m/s. Wind direction, which in raw data format is given in degrees ranging from 0-360, was grouped into eight categories, each representing a cardinal or ordinal direction (North, Northeast, East, Southeast, South, Southwest, West, Northwest). Wind direction was predominately from the south and southwest.

For further analysis, data were aggregated to 1-minute intervals to filter noise.

Orientation

The mean value of UFP was higher inside the bus shelter than outside the bus shelter when the shelter was oriented towards the roadway and higher outside the bus shelter than inside the bus shelter when the shelter was oriented away from the roadway. Like UFP, $PM_{1.0}$-PM_{10} concentrations were higher inside the bus shelter when the shelter was oriented towards the roadway, and higher outside when the shelter was oriented away from the roadway.

When the shelter faces the roadway, measurements inside the shelter were, on average across all particulate levels, 29 percent *more* than measurements outside the shelter. In contrast, when the shelter faces away from the roadway, measurements inside the shelter were one percent *less* than measurements outside the shelter.

Fig. II 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 March 22 for Locations 1, 2, and 3, respectively. Data are averaged to 5-minute intervals. Shelters facing towards the roadway (Locations 2 and 3) display opposing trends compared to 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.

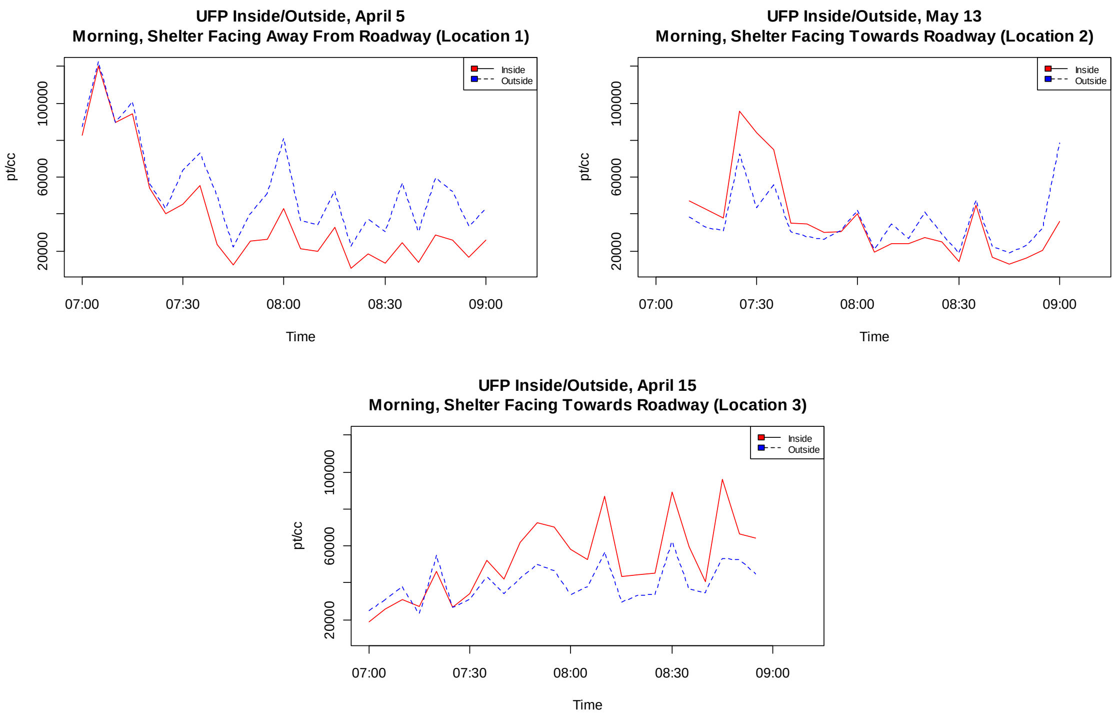
One-sided paired t-tests were used to evaluate whether particulate levels inside the bus shelter were significantly different than particulate levels outside the shelter. Particulate levels were found to be significantly greater (α=0.05) inside the bus shelter when the shelter faces towards the roadway, and significantly greater outside the bus shelter when the shelter faces away from the roadway.

Peaks in concentration are of special interest when considering damaging health effects related to short, intense bursts of exposure (Michaels and Kleinman 2000). Chi-square tests of independence were used to evaluate whether concentration spikes were significantly different inside the shelter than outside the shelter. The magnitude of particulate concentration spikes was found to be statistically different (α=0.05) inside and outside the bus shelters for all particulate sizes with the exception of UFP.

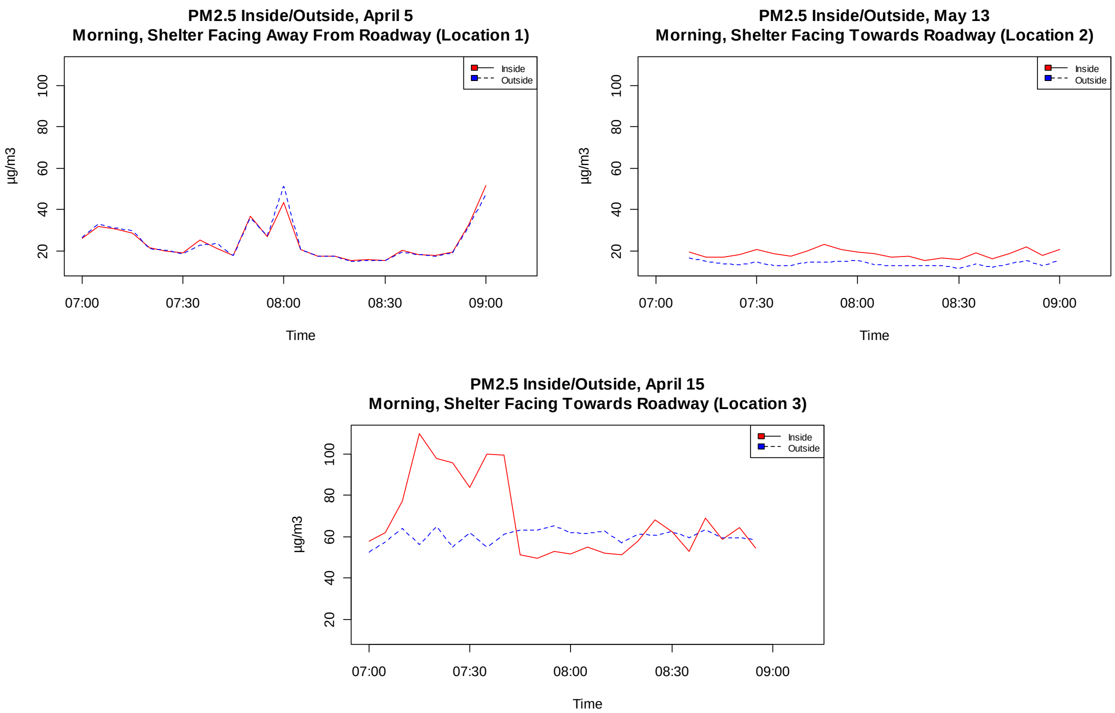
Table V Summary Statistics, All Data

	Morning					Evening				
	Mean	Median	Min	Max	St. Dev.	Mean	Median	Min	Max	St. Dev.
	Location 1									
UFP	39,516 *48,600*	27,283 *39,374*	7,493 *12,778*	162,242 *157,374*	30,438 *28,932*	17,239 *20,799*	14,756 *17,238*	7,194 *7,988*	64,574 *72,067*	9,630 *11,399*
$PM_{1.0}$	22.00 *19.37*	19.01 *17.50*	11.75 *6.19*	68.39 *87.00*	8.80 *10.55*	8.66 *11.82*	7.49 *10.66*	3.93 *6.66*	25.87 *41.80*	4.31 *4.63*
$PM_{2.5}$	23.17 *20.35*	20.10 *18.63*	11.82 *6.32*	70.77 *89.14*	8.98 *10.91*	8.75 *11.95*	7.60 *10.77*	3.99 *6.70*	25.96 *41.95*	4.32 *4.64*
PM_{10}	29.54 *22.23*	26.88 *20.32*	12.51 *7.24*	82.52 *91.61*	10.21 *11.05*	10.38 *13.35*	9.22 *12.23*	4.51 *7.52*	27.90 *43.10*	4.66 *4.87*
Vehicles	1356	1380	240	2580	464	1541	1560	540	3000	413
Heavy Veh	117	120	0	540	107	151	120	0	420	90.40
Temperature	5.14	5.17	4.5	6.17	0.51	12.99	12.94	12.17	13.61	0.41
Rel. Humidity	88	89	80	91	2.99	54	54	52	57	1.24
Wind Speed	0.97	0.95	0.44	1.75	0.36	(NA)				
	Location 2									
UFP	43,636 *45,786*	37,508 *43,303*	11,190 *15,540*	256,243 *154,073*	28,933 *22,659*	12,744 *10,392*	11,735 *9,556*	4,655 *5,679*	45,529 *36,344*	5,305 *3,651*
$PM_{1.0}$	39.71 *13.30*	44.08 *12.99*	14.22 *10.66*	82.56 *17.33*	21.68 *1.60*	10.54 *11.56*	10.63 *12.82*	4.77 *4.75*	35.80 *27.10*	3.84 *4.38*
$PM_{2.5}$	40.17 *13.60*	44.40 *13.31*	14.61 *10.96*	83.24 *17.67*	21.70 *1.61*	10.75 *11.70*	10.83 *12.95*	4.90 *4.81*	36.02 *27.43*	3.87 *4.42*
PM_{10}	43.62 *17.67*	47.20 *17.31*	16.86 *13.96*	88.22 *25.49*	22.52 *2.08*	13.23 *14.93*	13.73 *17.11*	5.78 *6.06*	38.61 *51.00*	4.61 *5.94*
Vehicles	1263	1260	60	2820	626	1365	1260	120	3300	708
Heavy Veh	158	120	0	600	138	146	120	0	720	140
Temperature	4.57	2.36	-0.11	9.56	3.97	18.53	15.61	15.28	22.78	3.14
Rel. Humidity	83	89	71	91	0.08	30	29	26	35	2.68
Wind Speed	0.74	0.74	0.16	1.30	0.25	1.02	0.96	0.39	2.03	0.66
	Location 3									
UFP	53,612 *44,352*	48,690 *40,654*	18,287 *15,980*	161,844 *108,772*	24,210 *17,784*	44,127 *32,312*	37,878 *27,450*	13,602 *7,553*	161,267 *119,000*	25,894 *17,401*
$PM_{1.0}$	45.77 *41.57*	48.75 *52.70*	15.69 *14.18*	171.83 *87.24*	28.69 *20.21*	10.39 *9.06*	9.96 *8.69*	4.73 *4.28*	25.02 *20.61*	3.41 *2.94*
$PM_{2.5}$	47.22 *41.97*	49.18 *52.87*	16.51 *14.70*	178.68 *87.45*	30.22 *20.08*	10.70 *9.31*	10.39 *9.00*	4.84 *4.37*	25.55 *20.72*	3.46 *2.96*
PM_{10}	52.12 *44.49*	50.14 *53.92*	18.16 *18.05*	308.65 *89.18*	40.46 *19.35*	12.27 *12.32*	12.28 *12.51*	5.13 *5.02*	27.93 *24.61*	3.89 *3.94*
Vehicles	1037	960	60	2940	584	1378	1290	240	2880	708
Heavy Veh	46	0	0	300	70	51	0	0	480	81
Temperature	5.61	6.39	4.22	6.94	1.13	10.45	10.89	9.39	11.56	0.92
Rel. Humidity	90	94	84	94	4.3	73	57	49	94	20
Wind Speed	(NA)					0.64	0.62	0.21	1.22	0.20

NA = Not Available



(a)



(b)

Fig. II Morning (a) UFP and (b) $PM_{2.5}$ concentrations inside and outside the bus shelter per 1-minute time intervals at each shelter location.

Time of Day Patterns

Diurnal concentration levels reflect higher morning concentrations, similar to results found in other studies (Adams, Nieuwenhuijsen, and Colvile 2001; Adams et al. 2001; Hess et al. 2010). Morning concentrations were, on average, 227% higher than evening concentrations across all particulate levels and all shelter sampling locations. Such patterns were attributed to changes in temperature and humidity throughout the day, but may also be explained by morning and evening peak hour traffic flow. Two shelters are located on the westbound (inbound to CBD) side of Powell Boulevard, and one is located on the eastbound (outbound from CBD) side. Table VI shows the ratio of morning and evening concentrations at each shelter.

Table VI Morning vs. Evening Concentration Ratios for Each Shelter Location

Date	UFP	$PM_{1.0}$	$PM_{2.5}$	PM_{10}
	Location 1 (morning peak)			
April 5	(evening data unavailable)			
April 29	1.73	1.71	1.71	1.61
	Location 2 (morning peak)			
April 8	4.73	7.43	7.37	6.26
May 13	2.98	1.11	1.12	1.09
	Location 3 (evening peak)			
March 22	1.48	2.17	2.15	1.78
April 15	1.00	7.87	7.05	6.99

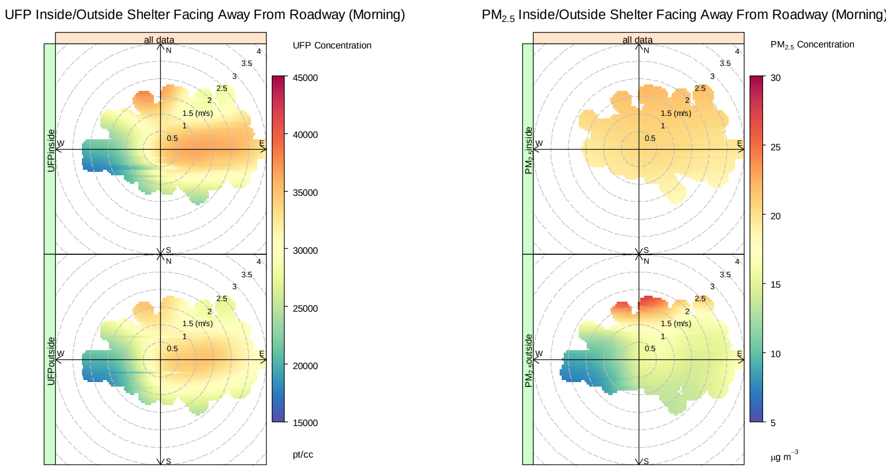
Wind Speed and Direction

Fig. III shows sample plots of observed concentrations of UFP and $PM_{2.5}$ varying by wind speed and direction at each shelter location using polar plots 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 based on 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 represent inside (top) and outside (bottom). For instance, the UFP concentrations at Location 1 are highest when the wind is from the east. Shelter orientation relative to cardinal directions is given in the figure descriptions. The plots in Fig. III were created using the OpenAir package in the statistical software program R (Carslaw and Ropkins 2011).

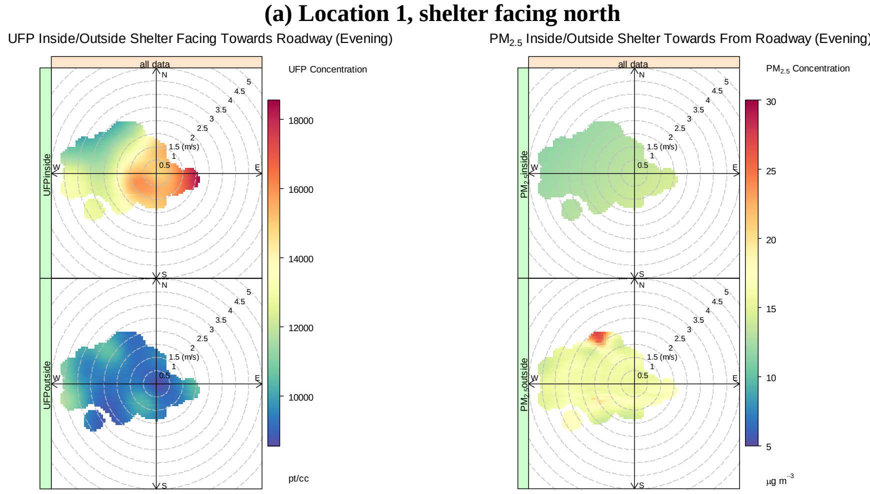
The figure indicates UFP concentrations are at their highest when winds are from the east (Fig. III (a), shelter facing north) and from the southwest (Fig. III (c), shelter facing north). $PM_{2.5}$ concentrations are highest when winds are from the north, though Fig. IIIc shows $PM_{2.5}$ concentrations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

Wind direction affects particulate concentrations differently in each shelter location and for each shelter orientation. Fig. IIIc best illustrates discrepancies in particulate behavior: UFP concentrations inside and outside the shelter are equally affected by wind direction, as evidenced by the highest concentrations, which are always affected by westerly winds, increasing with intensity. At the same time, $PM_{2.5}$ concentrations appear to be unaffected by wind direction outside the shelter, indicated by uniform hues in all directions, while concentrations inside the shelter are minimally affected by easterly wind directions at very low wind speeds, evidenced by slightly higher hues.

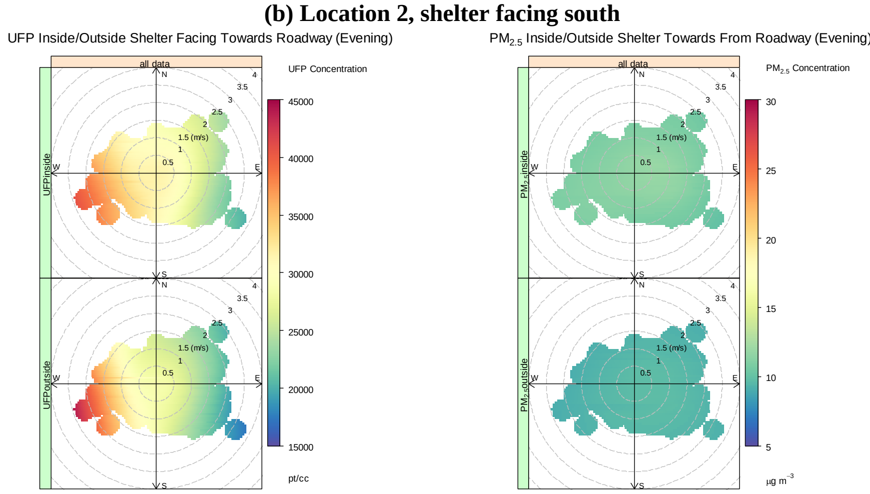
Increasing wind speed generally results in lower concentrations, although this is not always the case. UFP concentrations inside the shelter in Fig. III (c) increase with wind speed, indicating potential entrapment of particles within the shelter. $PM_{2.5}$ concentrations inside the shelter at the same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



(a) Location 1, shelter facing north

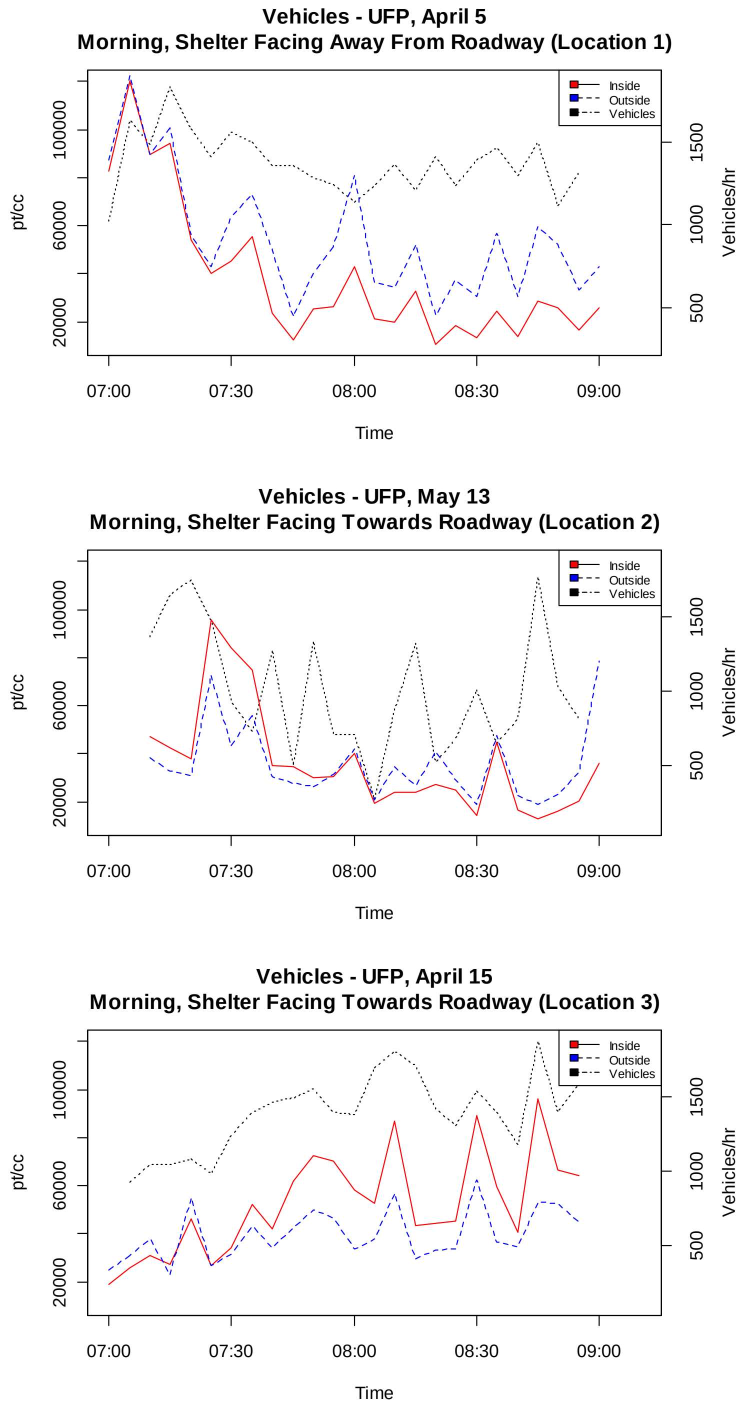


(b) Location 2, shelter facing south

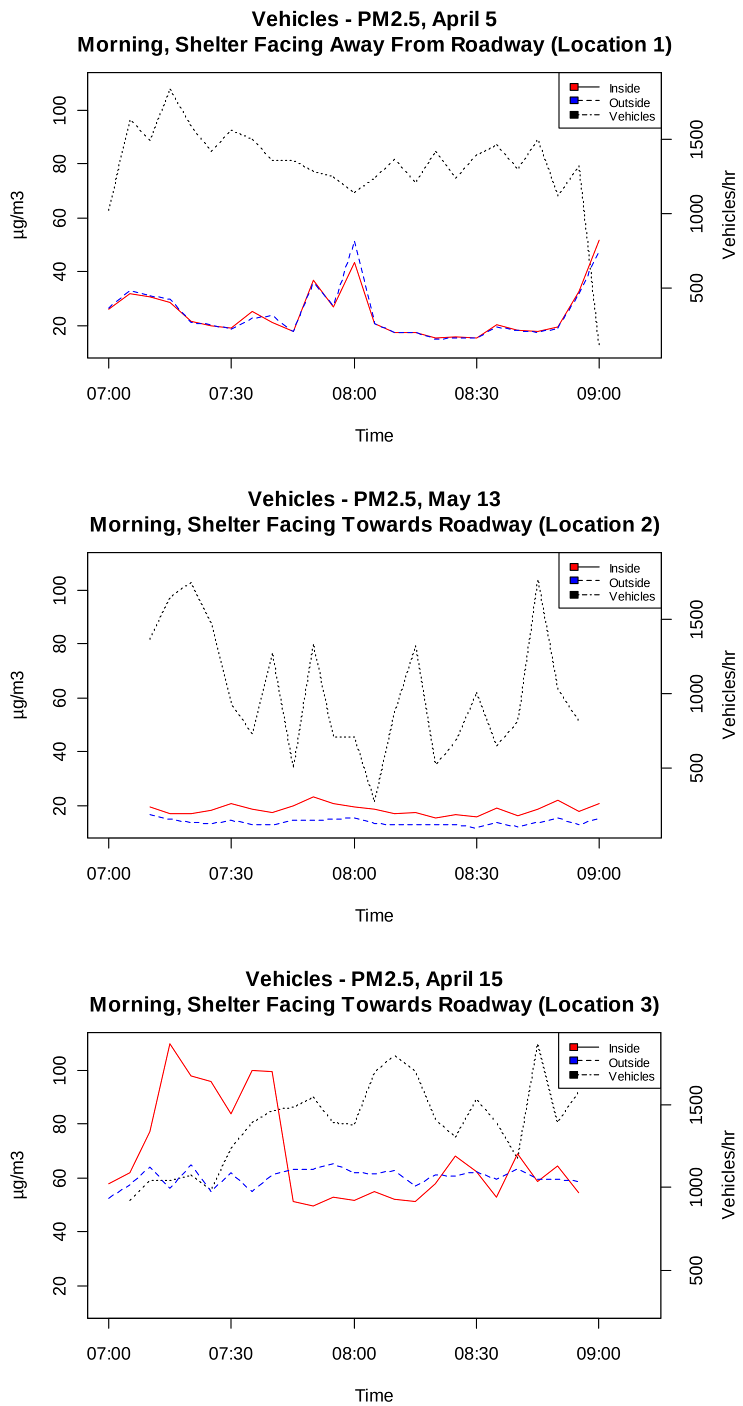


(c) Location 3, shelter facing north

Fig. III Bivariate polar plots illustrating wind speed and direction effects on UFP and $PM_{2.5}$ concentrations at each location.


Vehicles - UFP, April 5
Morning, Shelter Facing Away From Roadway (Location 1)
Inside
Outside
Vehicles
pt/cc
20000
60000
100000
Vehicles/hr
500
1000
1500
07:00
07:30
08:00
08:30
09:00
Time
Vehicles - UFP, May 13
Morning, Shelter Facing Towards Roadway (Location 2)
Vehicles - UFP, April 15
Morning, Shelter Facing Towards Roadway (Location 3)

(a)



(b)

Fig. IV Morning UFP (a) and evening $PM_{2.5}$ (b) concentrations at each bus shelter location overlaid with hourly vehicle flow per 1-minute time intervals.

Vehicle Flow

Vehicle flow data were recorded during each sampling period. The RTMS unit was calibrated to record vehicle counts every five seconds for the direction of travel closest to the bus stop shelter. At Location 1, three lanes in the westbound direction, including one left turn lane, were monitored. Location 2 was the same as Location 1. At Location 3, three lanes in the eastbound direction were monitored.

Fig. IV shows a sample of vehicle flow and either morning UFP concentrations (Fig. IV (a)) or evening $PM_{2.5}$ concentrations (Fig. IV (b)) inside and outside bus shelter locations. Particulate concentrations are averaged to 5-minute intervals. Vehicle counts are shown in 5-minute aggregated intervals. In several cases, upward traffic trends were observed, in which traffic flow gradually rises from 7:00 am – 8:00 am before leveling off.

The morning sampling period at Location 2 exhibits a downward trend in vehicle flow until 8:00 am followed by a gradual rise that continues until the end of the sampling period at 9:00 am. Such a traffic flow pattern is unexpected; Location 2 is positioned on the inbound traffic side of the road and traffic volumes are expected to be at their highest in the morning rush hour between 7:00 am – 9:00 am.

Correlation

To investigate the relationship with independent variables further, the Pearson coefficient correlations between vehicle, weather, and particulate variables were explored. Vehicle flow was subdivided into vehicles (all vehicles) and heavy vehicles (vehicles with length > 6 m). Very high correlations (> 0.95) were observed between $PM_{1.0}$, $PM_{2.5}$, and PM_{10}. Hence, only $PM_{2.5}$ is reported in this section. Select results are presented in **Table VII**.

Table VII Select Pearson coefficient correlation results for each location, inside and outside shelter

	Inside				Outside			
	UFP		$PM_{2.5}$		UFP		$PM_{2.5}$	
	Location 1, Evening (April 29)							
n	111				106			
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Vehicles	0.013	0.892	0.038	0.694	-0.012	0.901	-0.039	0.689
Heavy Veh	0.068	0.479	-0.065	0.500	0.036	0.717	0.009	0.928
Temperature	**-0.289**	0.002	0.037	0.702	**-0.259**	0.007	0.015	0.877
Rel. Humidity	0.106	0.267	0.083	0.386	0.054	0.580	0.139	0.156
Wind Speed	-	-	-	-	-	-	-	-
	Location 2, Evening (May 13)							
n	120				118			
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Vehicles	-0.024	0.795	-0.080	0.385	-0.011	0.906	-0.105	0.256
Heavy Veh	-0.106	0.248	0.077	0.401	0.055	0.551	-0.059	0.523
Temperature	**-0.263**	0.004	**-0.257**	0.005	**0.531**	0.000	**-0.302**	0.000
Rel. Humidity	**0.293**	0.001	**0.400**	0.000	**-0.494**	0.000	**0.257**	0.005
Wind Speed	**-0.239**	0.008	-0.145	0.114	0.118	0.205	-0.004	0.965
	Location 3, Morning (March 22)							
n	106				106			
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Vehicles	0.034	0.728	0.071	0.467	0.066	0.500	0.066	0.503
Heavy Veh	-0.054	0.584	-0.066	0.504	-0.086	0.383	-0.027	0.787
Temperature	**0.336**	0.000	-0.107	0.274	**0.276**	0.004	-0.056	0.567
Rel. Humidity	**-0.321**	0.000	0.138	0.157	**-0.289**	0.003	0.111	0.256
Wind Speed	-	-	-	-	-	-	-	-

r = Pearson correlation coefficient, *p* = observed significance level, bold *r*-values indicate significance at p = 0.05 level

Temperature and relatively humidity had the most significant correlations with both UFP and $PM_{2.5}$. Temperature and humidity have correlations with opposite signs. Pearson coefficients for temperature ranged from r = -0.289 to r = 0.531. Relative humidity was also highly significant in some instances. Wind speed significantly affected UFP, and it should be noted that more wind speed data may have led to further insights. No significant correlation was found for vehicles or heavy vehicles.

Because April 15 exhibited a possible correlation of interest, see Fig. IV (a), was investigated further. Vehicle flow was shown to be positively and significantly correlated with UFP concentrations inside the shelter, but not outside the shelter. $PM_{2.5}$ concentrations did not exhibit a significant correlation. Temperature was shown to be significantly correlated with both particulate sizes. Humidity was not analyzed due to a lack of measurements. Wind speed was not collected for this sampling date.

Table VIII April 15 Pearson correlation coefficients

	Inside				Outside			
	UFP		$PM_{2.5}$		UFP		$PM_{2.5}$	
	Location 3, Morning (April 15)							
n	115				115			
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Vehicles	**0.212**	0.023	-0.161	0.086	0.077	0.412	0.011	0.903
Heavy Veh	0.067	0.476	-0.024	0.797	0.002	0.986	0.147	0.118
Temperature	**0.485**	0.000	**-0.385**	0.000	**0.247**	0.008	0.052	0.584
Rel. Humidity	(NA)		(NA)		(NA)		(NA)	
Wind Speed	(NA)		(NA)		(NA)		(NA)	

NA = Not Available

Discussion

The analysis suggests that the variables investigated in this study play a significant role in particulate concentration levels surrounding bus stop shelters. Time and location; orientation to the roadway; and traffic and weather were all shown to significantly influence concentrations. Previous studies have reinforced the influence of variables categorized in this study as “time and location,” “weather,” and “vehicles,” at least to a degree. This study, however, is among the first to investigate the role shelter orientation plays in particulate concentration levels.

Particulate concentrations were significantly greater inside the shelter than outside the shelter when facing towards the roadway. In contrast, particulate concentrations were significantly greater outside the shelter than inside when facing away from the roadway. Orienting a shelter away from the roadway has the potential to aid in shielding bus patrons from particulate matter compared to a shelter facing towards the roadway.

Orientation is an issue due to the 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 particulate 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. This effect is shown in Fig. II (a) as spikes in concentration are typically less inside the shelter at Location 1, indicating a “buffer” or “dilution” effect. Such buffer effects are particularly important at shelters very close to the roadway (less than five feet), as is the case at Location 1. Shelters situated within close proximity to the roadway would be exposed to the highest particulate concentrations that have not yet dispersed over greater distances.

Shelters located on the far-side of an intersection (Locations 1 and 2) were shown to have significantly higher particulate concentrations than near-side shelters (Location 3). This was an unexpected outcome, given that vehicles are regularly idling close to near-side shelters as drivers wait for a signal change. Location 3 does not see the highest overall AADT, either; Location 1 sees slightly higher daily vehicle counts, as well as heavy vehicle counts. The built environment is not substantially different at Location 3, with one exception: the presence of a gas station, a point source for particulate air pollution, across the street from the shelter. A gas station may explain the bias towards far-side shelter concentration. Unfortunately, only one far-side shelter was examined in this study; more far-side shelters will need to be investigated before definitive conclusions can be made about the influence of shelter location relative to the intersection on particulate concentration levels.

Vehicle flow was shown to significantly affect UFP, though to a smaller degree than would be expected based on apparent correlation indicated in Fig. IV. Significance was expected based on a review of literature, though this study is considerably less comprehensive than past studies in terms of documenting vehicle presence. The RTMS unit used to measure vehicle activity was not capable of monitoring the entire roadway, instead only monitoring the direction of travel closest to the shelter. In effect, this study monitored just half of the roadway environment.

A limited investigation of vehicle classification effects on particulates was conducted by isolating heavy vehicle flow as a variable. No significance was found for such vehicles, though this is likely attributable to a lack of observed instances more than it is an accurate representation of heavy vehicle influences. Over the course of all data collections, considerably fewer heavy vehicles were recorded (N=3509) compared to all vehicles (N=19995). Previous literature has shown a definite influence of large, diesel-powered vehicles on particulate concentrations, especially UFP.

Further investigation will need to consider a more detailed vehicle classification variable, which may help to explain spikes in concentration such as the $PM_{2.5}$ spikes at Location 3 (Fig. IV (b)).

Evening particle concentrations are significantly lower on average than morning concentrations. In conjunction with traffic data, consideration must be made for shelter location on the inbound (westbound) or outbound (eastbound) roadside; that is, whether a roadway next to the shelter will see larger morning or evening traffic volumes. Shelters sited along the inbound roadway lanes (Locations 1 and 2) may experience lower particulate levels in the evening due to lower vehicle volumes.

Limitations

The primary limitation of this study involves accuracy of wind measurements and the ability of these measurements to represent the entirety of the environment surrounding the bus shelter. The anemometer, while consistently placed in the same location at each shelter, was ultimately determined to be a weak indicator of wind speed and direction at all points in proximity to the study location. In a complicated near-road environment, wind is affected by myriad factors ranging from tail winds of tractor-trailers to turbulence created by trees and signposts. Thus, the measurements presented can only be said to represent wind's influence on particulate levels *at that exact location*. Though this may initially appear to severely limit the usefulness of the wind data, it is important to note that the anemometer was placed adjacent to the particulate monitors outside the shelter and as such the data constitutes a fair representation of particulate dependence on wind speed and direction for passengers waiting outside bus stop shelters.

The sidewalls of the shelter may play a role in shielding efficiency of a shelter that faces away from the roadway. Along the study corridor, available shelter types limited complete comparisons between shelters towards and away from the roadway.. The shelter facing away from the roadway in this study had shorter walls (~2 feet long) than the shelters facing the roadway (~4 feet long). It is possible that the volume of air contained in the shelter, which is less than a shelter with longer walls, could affect particulate concentration levels. This 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.

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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 studies will need to consider other variables to effectively control for as many factors as possible when determining the significance of varying particulate levels. Many factors could affect the concentration levels, including coordinated signals along a corridor, percentage of heavy vehicles on the roadway, and distance to curb. Air quality data will need to be synchronized with these missing factors to most accurately determine relationships between particulate levels, traffic volume and vehicle type, and the surrounding built environment.

Conclusions

Particulate matter, as a common air pollutant recognized by NAAQS, is a key contributor to urban air quality-health concerns. Understanding roadside particulate exposure requires detailed measurements in complicated microenvironments. This study uses a comparative approach to determine particulate matter 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 author's 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 particulate matter levels and, consequently, exposure.

Other variables failed to display consistently significant correlations with any particulate sizes. Further analysis of these variables will help to create a more robust understanding of a microenvironment's effects on particulate concentrations.

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 the 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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