Statistical Study of Variables Associated with Particulate Matter Exposure Levels at Bus Shelters

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This study expands on previous work that examined differences in exposure to particulate matter in and around bus stop shelters for passengers waiting along a busy urban corridor in Portland, Oregon. An extensive body of literature has demonstrated the negative health effects of exposure to particulate matter. Although concentrations of particulate matter were known to be greater near busy roadways, little research has been conducted on exposure in and around bus stop shelters. Two sizes of particulate matter were examined in this study: fine particulate matter of less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) and ultrafine particles. Pearson association tests were run between particulate concentrations and three categories of independent variables: location, traffic, and weather. Significant correlations were observed primarily between particulates and weather (temperature and relative humidity). With 1-min data intervals, a series of log-linear regression models with and without lagged variables was used to estimate the effects of location, traffic, and weather variables on particulate concentrations. The presence of a transit bus stopped at the shelter significantly increased both sizes of particulate matter concentrations. Wind, temperature, and shelter location also had significant effects on ultrafine and $PM_{2.5}$ levels. The estimated models for particulate concentrations inside and outside the bus stop shelters were compared to demonstrate differences in particulate behavior. Suggestions are made for shelter configuration given environmental and traffic considerations.

Urban air quality is a rising concern for the general public, demanding focused research to better understand and mitigate health risks and to improve the quality of life. Transport microenvironments (a small-scale environment comprising the roadway and its immediate surroundings) have been linked to higher levels of air pollution and thus higher levels of exposure compared with background concentrations (*1, 2*). Travelers using public transportation along busy arterial corridors may be exposed to greater-than-average levels of air pollution because of their proximity to high volumes of motor vehicles while waiting for a bus.

Particulate matter (PM) is a component of vehicle exhaust and one of six common air pollutants regulated by the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS). PM pollution is present at elevated levels along busy roadways. PM is generally classified by the largest aerodynamic diameter of the particles in the composition. $PM_{2.5}$ and ultrafine particles (UFPs) have aerodynamic diameters of less than 2.5 µm and 0.1 µm, respectively. EPA sets annual average and 24-h average exposure limits for $PM_{2.5}$, most recently 15 µg/m^3 and 35 µg/m^3, respectively (NAAQS). UFPs are not regulated by EPA. Ambient $PM_{2.5}$ background concentrations are generally below 16 µg/m^3 (*3*). Ambient urban UFP background concentrations range from a few thousand to 20 thousand particles per cubic centimeter (*4*). Because of their small size, $PM_{2.5}$ and UFPs are able to penetrate deeply into the body's respiratory system. Previous research has demonstrated the negative health effects of exposure to PM, linking it to cardiac and respiratory symptoms, such as aggravation of asthma, chronic bronchitis, and decreased lung function (*4–7*).

TriMet, Portland's transit agency, operates a bus fleet composed of diesel buses running on a biodiesel fuel blend. Diesel engines are often singled out as significant sources of particulate matter (NAAQS). Diesel engines can emit 10 to 100 times more PM mass than gasoline engines (*8, 9*). PM emissions from diesel engines are regulated by EPA, most recently set at a maximum of 0.01 g/bhp-h (bhp = brake horsepower) (EPA Exhaust Emission Standards: Heavy-Duty Highway Compression-Ignition Engines and Urban Buses). Transit buses, most commonly diesel powered, have been studied to understand their effect on air quality in the transport microenvironment (*1, 10*). Many studies have focused on the bus itself, examining in-vehicle pollution exposure (*11–14*).

Little research has been conducted on the exposure of transit users in waiting areas, and fewer still have looked specifically at the design and placement of bus stop shelters as a significant determinant of exposure (*15, 16*). Although transit users typically spend only a small amount of time waiting for the bus, they are nevertheless in an environment with high concentrations of PM, and peak exposures such as this are thought to exacerbate existing health symptoms to a greater degree than ambient background pollutant levels (*17*).

This paper considers the various factors contributing to $PM_{2.5}$ and UFP concentrations in and around bus stop shelters. Previous work demonstrated a significant difference in particulate concentrations inside and outside the shelters, with significant differences by the direction of shelter orientation (*18*). Shelters oriented away from the roadway tended to reduce transit user's exposure levels. The present analysis expands on those findings and seeks to determine the contribution of location, traffic, and atmospheric variables on PM concentrations by using linear regression models. Previous studies of exposure at bus stop shelters have not included regression models with analysis of variable elasticity and contribution to exposure levels.

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(a) (b)

FIGURE 1 Shelter orientation: (*a*) toward roadway and (*b*) away from roadway.

DATA COLLECTION

The study area is Powell Boulevard, a four-lane east–west urban arterial roadway in Portland, Oregon, connecting the outlying suburbs to the east and the central business district to the west. The corridor is typified by one-, two- and three-story buildings set back from the roadway, often by parking lots. Three bus stop shelters, denoted as Locations 1, 2, and 3, are included in the study, each with a three-panel design, in which one long panel forms the back of the shelter and two shorter panels form the sides, as shown in Figure 1. The three bus stop shelters face either toward or away from the roadway. The details of the shelter environments are presented in Table 1. The largest differences in built environment characteristics between shelters are at Location 3; a gas station across Powell Boulevard and a larger cross street result in a higher-traffic intersection than at Locations 1 and 2. Shelters are located either nearside or farside with respect to the intersection. 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.

Monitoring devices were placed in and around the bus stop shelters to measure PM concentrations, weather conditions, and vehicle flow. All data were collected in two sessions at each of the three study shelters; a session consists of the morning peak (7:00 to 9:00 a.m.) or evening peak (4:00 to 6:00 p.m.) periods. Data were collected in spring 2011.

PM concentrations were measured simultaneously inside and outside the bus stop shelters. $PM_{2.5}$ measurements were made by using two DustTrak DRX Aerosol Monitors (TSI Model 8533) capable of measuring concentrations between 1 and 150,000 $\mu g/m^3$. UFP measurements were made with two P-Trak Ultrafine Particle Counters (TSI Model 8525), capable of measuring concentrations

TABLE 1 Study Location Details

Characteristic	Location 1	Location 2	Location 3
Shelter orientation	Away from roadway	Toward roadway	Toward roadway
Eastbound–westbound on Powell Boulevard	Westbound (inbound)	Westbound (inbound)	Eastbound (outbound)
Cross street	21st Avenue	26th Avenue	39th Avenue
Cross street lanes	2	2	4
Nearside–farside	Nearside	Nearside	Farside
Distance to curb (m)	0.6	2.7	3.8
Powell Boulevard annual average daily traffic (2009)[a]	35,300	31,500	34,100
Percentage of trucks, morning[b] (Powell)	12.4%	18.6%	4.5%
Percentage of trucks, evening[b] (Powell)	9.7%	17.1%	5.5%
Average bus headway, morning	8 min	8 min	20 min
Average bus headway, evening	15 min	15 min	7 min
Average boardings per hour, morning	1.2	1.0	1.9
Average boardings per hour, evening	1.6	1.9	2.8

[a]http://www.oregon.gov/ODOT/TD/TDATA/tsm/docs/2009_TVT.pdf.
[b]Vehicle length > 6 m, as observed during data collections.

up to 500,000 particles/cm^3 (pt/cc) and particle sizes from 0.02 to 1 µm. Both sets of monitors were factory calibrated within a year before the start of data collections.

Wind speed and direction were measured with an RM Young Ultrasonic Anemometer (Young Model 81000) placed next to the outside location PM monitors. The anemometer could be used only during fair weather conditions and, as such, wind data were collected for just four sampling periods. Temperature and relative humidity data were gathered at a 1-min data resolution from a nearby weather station, located 2 km from Location 1 (farthest shelter) and 500 m from Location 3 (closest shelter).

Traffic speed, volume, and classification were collected by using an RTMS G4 unit (ISS Model K4-LV-CAM). Vehicle classification is inferred from vehicle length by the RTMS unit. Heavy vehicles were identified as any vehicle with a length greater than 6 m. The RTMS unit is designed for midblock operation and depends on vehicle movement for detection. To counter detection problems associated with vehicle queuing, the unit was placed approximately 60 to 70 ft away from the intersection crosswalk in an effort to avoid stopped vehicles. The RTMS unit was capable of recording traffic only in the direction of travel closest to the bus stop shelter.

Bus presence was collected during each sampling period by manually noting the arrival and departure of buses. A bus was marked as having arrived once it stopped in front of the shelter and as having departed once the rear of the bus passed the shelter.

Finally, the presence of smokers near the bus shelter was noted. However, these instances were very few. There were two documented cases of a smoker being within several meters of the bus shelter. These cases were excluded from the regression analysis.

Data were combined and organized into dependent and independent variables, described in Table 2. All data were aggregated to 1-min intervals, and all analysis was based on this level of resolution. Select vehicle and weather variables were lagged up to three periods to investigate delayed effects on particulate concentrations. Wind data are composed of wind speed and wind direction. Wind direction was split into four variables, each representative of a direction relative to the shelter and described in Table 2. Raw wind direction data were output at 1-s intervals. One-minute aggregations are composed of the percent of time the wind blew in one of the four directions during the previous minute.

Table 3 shows a summary of the data collected for all three locations. The mean UFP concentration for all data collected was 34,815 pt/cc. The mean value of $PM_{2.5}$ was 22.02 µg/m^3. These values are greater than expected ambient background concentrations and are in line with existing literature results for near-road conditions in an urban environment (*11, 19, 20*). Maximum concentrations are substantially higher.

Vehicle flow averaged 1,285 vehicles per hour. This unit of measure is not vehicles per hour per lane. Rather, this is a sum of all three lanes of travel in the direction closest to the shelter. Temperature averaged 49°F, with a wide range (31°F–73°F) indicative of changing meteorological conditions between average morning (41°F) and evening (58°F) sampling times. Similarly, relative humidity ranged from 26% to 94%, averaging 71%. Morning average relative humidity was 87%, and evening average relative humidity was 51%. Wind speed averaged less than 1 m/s, a low value but reasonable given that measurements were made at street level.

CORRELATION ANALYSIS

Previous work demonstrated a significant difference in particulate concentrations inside and outside the shelters with the dependent variables from this data set (*18*); statistical results also showed a

TABLE 2 Variable Definitions

Variable	Definition	Unit
Dependent Variables		
UFP	Continuous variable describing concentration	pt/cc
$PM_{2.5}$	Continuous variable describing concentration	µg/m^3
Independent Variables		
Location	Dummy variables for Location 1, 2, or 3	na
Vehicles		
Vehicle flow	Total number of vehicles passing shelter; in-period and lagged up to 3 periods	veh/h
Heavy vehicle (truck) flow	Number of heavy vehicles passing shelter (defined as length >6 m); in-period and lagged up to 3 periods	veh/h
Bus presence	Dummy variable	na
Weather		
Wind speed	Average wind speed; in-period and lagged up to 3 periods	m/s
Wind direction—toward shelter	Percentage of time wind blows toward the shelter over a 1-min interval; in-period and lagged up to 3 periods	%
Wind direction—away from shelter (reference)	Percentage of time wind blows away from the shelter over a 1-min interval; in-period and lagged up to 3 periods	na
Wind direction—with the direction of traffic	Percentage of time wind blows in the direction of traffic closest to the shelter over a 1-min interval; in-period and lagged up to 3 periods	%
Wind direction—against the direction of traffic	Percentage of time wind blows against the direction of traffic closest to the shelter over a 1-min interval; in-period and lagged up to 3 periods	%
Temperature	Temperature at nearby weather station	°F
Relative humidity	Relative humidity at nearby weather station	%

NOTE: na = not applicable.

TABLE 3 Summary Statistics

Variable	Mean	Median	Minimum	Maximum	SD
Location 1, $N = 670$ (shelter facing away from roadway)					
UFP (pt/cc)					
Inside	30,226	21,803	7,344	162,242	23,798
Outside	36,862	28,078	8,064	157,374	25,970
$PM_{2.5}$ (µg/m^3)					
Inside	17.13	16.71	4.02	70.77	9.72
Outside	17.22	15.27	6.19	89.14	9.55
Vehicle flow (veh/h)	1,374	1,320	240	2,580	509
Heavy vehicle flow (veh/h)	121	120	0	480	104
Temperature	46	42	40	57	7
Relative humidity (%)	76	86	52	91	16
Wind speed (m/s)	0.90	0.84	0.35	1.62	0.30
Location 2, $N = 932$ (shelter facing toward roadway)					
UFP (pt/cc)					
Inside	27,549	17,359	4,508	256,243	25,590
Outside	27,365	16,083	5,406	153,094	23,782
$PM_{2.5}$ (µg/m^3)					
Inside	24.89	15.30	4.81	83.24	21.20
Outside	12.28	13.26	4.63	27.48	3.89
Vehicle flow (veh/h)	1,312	1,320	60	2,820	591
Heavy vehicle flow (veh/h)	151	120	0	600	144
Temperature	53	60	32	73	14
Relative humidity (%)	55	35	26	91	27
Wind speed (m/s)	0.88	0.84	0.16	1.96	0.33
Location 3, $N = 860$ (shelter facing toward roadway)					
UFP (pt/cc)					
Inside	49,040	43,497	13,602	161,844	25,586
Outside	38,515	34,639	7,389	121,753	18,764
$PM_{2.5}$ (µg/m^3)					
Inside	29.54	18.74	4.84	178.69	28.39
Outside	26.19	17.14	4.39	87.45	21.81
Vehicle flow (veh/h)	1,194	990	60	3,180	713
Heavy vehicle flow (veh/h)	49	0	0	480	77
Temperature	46	45	40	53	5
Relative humidity (%)	83	94	49	94	16
Wind speed (m/s)	0.64	0.61	0.24	1.24	0.21

NOTE: SD = standard deviation.

significant difference between inside and outside concentrations as a function of shelter orientation. Shelters oriented away from the roadway tend to reduce transit user exposure levels inside the shelter by 1% versus outside the shelter; shelters oriented toward the roadway tend to increase transit user exposure levels inside the shelter by 29% versus outside the shelter. This analysis expands on those findings and seeks to determine the distinct contributions of location, traffic, and weather variables on PM concentrations, by using linear regression models.

Initially, the dependent data were checked for normality using quantile–quantile (Q-Q) plots, and both variables were found to be skewed. As in previous research efforts, dependent variables were log-transformed to compensate for skewness (*21*). Testing again for normality after log transformation, Q-Q plots for both variables suggested normal distributions. Dependent variables are thus logged for the rest of this paper. To investigate pairwise correlations between each particulate size and the independent variables, a Pearson test for association ($\alpha = 0.05$) was performed between each vehicle and weather variable and each logged particulate variable. Results are presented in Table 4.

The strongest predictors in the correlation analysis, temperature and humidity, were also the most global. More local variables, that is, vehicles and wind, were less correlated. Significant correlations were consistently observed for temperature and relative humidity for UFPs and $PM_{2.5}$. In most instances, temperature was negatively correlated. Relative humidity was consistently observed to have a significant positive correlation with both particulate sizes. Vehicles, heavy vehicles, and wind speed and direction were inconsistently correlated, and few conclusions could be drawn about shelter design.

The inconsistencies in these results indicate the complexity of the environment surrounding the bus stop shelters. Correlations alone are not enough to explain the relationship between multiple independent variables and particulate concentrations. Linear regression models were thus estimated to further analyze the relationships between location, traffic, and meteorological variables.

TABLE 4 Association Correlation Test

	Inside				Outside			
	logUFP		$logPM_{2.5}$		logUFP		$logPM_{2.5}$	
Variable	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Location 1 (shelter facing away from roadway)								
Vehicles	−.04	.464	**−.13**	.040	−.03	.591	−.03	.591
Heavy vehicles	**−.15**	.008	**−.15**	.022	**−.14**	.018	−.06	.310
Wind speed	−.04	.660	−.08	.549	−.04	.708	.01	.949
Wind direction								
TS	−.07	.457	.07	.609	−.04	.653	−.05	.614
AS	−.04	.682	.00	.991	−.01	.895	.21	.041
WT	.19	.055	−.03	.844	.15	.123	.09	.406
AT	−.15	.130	.00	.988	−.14	.165	−.27	.007
Temperature	**−.43**	<.001	**−.69**	<.001	**−.46**	<.001	**−.41**	<.001
Relative humidity	**.43**	<.001	**.69**	<.001	**.47**	<.001	**.43**	<.001
Location 2 (shelter facing toward roadway)								
Vehicles	.03	.476	**.13**	.006	.03	.478	**.27**	<.001
Heavy vehicles	.00	.928	.06	.183	.03	.461	.02	.688
Wind speed	**−.29**	<.001	**−.42**	<.001	**−.32**	<.001	.02	.787
Wind direction								
TS	.10	.133	**.33**	<.001	**.23**	<.001	.08	.375
AS	−.07	.301	**−.16**	.012	−.10	.112	−.03	.782
WT	.08	.219	**.29**	<.001	**.18**	.006	**.23**	.013
AT	−.05	.412	**−.26**	<.001	**−.18**	.007	−.03	.736
Temperature	**−.61**	<.001	**−.84**	<.001	**−.80**	<.001	**.23**	<.001
Relative humidity	**.64**	<.001	**.82**	<.001	**.79**	<.001	**.31**	<.001
Location 3 (shelter facing toward roadway)								
Vehicles	−.09	.064	.04	.460	**−.16**	.001	.07	.148
Heavy vehicles	.01	.827	**.13**	.005	−.03	.493	**.17**	<.001
Wind speed	−.11	.252	−.03	.730	−.05	.601	−.02	.813
Wind direction								
TS	.04	.722	.09	.353	−.02	.863	−.03	.741
AS	−.07	.511	−.03	.771	−.11	.270	−.02	.819
WT	.05	.636	−.12	.238	.07	.488	−.14	.157
AT	−.01	.931	.06	.518	−.05	.635	.16	.108
Temperature	**−.24**	<.001	**−.42**	<.001	**−.37**	<.001	**−.49**	<.001
Relative humidity	**.38**	<.001	**.40**	<.001	**.24**	<.001	**.47**	<.001

NOTE: *r* = Pearson correlation coefficient; *p* = observed significance level; TS = toward shelter; AS = away from shelter; WT = with traffic; AT = against traffic. Bold *r*-values indicate significance at *p* = .05 level.

LINEAR REGRESSION RESULTS

Models were specified for both particulate sizes inside and outside the shelter, for a total of four models. The models presented in this paper present variables significant at $\alpha = 0.05$. The final model specifications are presented in Tables 5 and 6.

The final models were estimated in two steps. First, all variables, including lagged variables and interactions between groups of variables, were included in the model. Vehicle flow was tested for interaction with wind speed and wind direction to compare particulate levels when wind blows toward the shelter as vehicle volume varies. The location variables were tested for interaction with wind-related variables to compare wind effects for a shelter facing away from the roadway versus toward the roadway. For the second step of the estimation process, variables that were nonsignificant (at $\alpha = 0.05$) were removed sequentially. In several instances during model specification, temperature and relative humidity were both significant, but the coefficient sign of one was the opposite of expected. For example, temperature and relative humidity both had negative coefficients in the model for UFPs inside the shelter, indicative of high correlation and near multicollinearity. To correct the issue, one of the two variables was removed—whichever had the least effect on the overall model.

UFP levels inside the shelter were expected to decrease by 3% on average per degree Fahrenheit increase in temperature, holding constant all other variables. $PM_{2.5}$ levels inside the shelter were expected to decrease an average of 2% per degree Fahrenheit increase in temperature, holding constant all other variables. Wind speed and direction were irregularly significant. Wind speed was significant in the model only for UFPs inside the shelter. The coefficient sign was consistent with expectations, and UFP levels were expected to decrease an average of 19% with a 1 m/s increase in wind speed, holding constant all other variables.

TABLE 5 Log-Linear UFP Regression Model

Variable	Coefficient	SE	*p*
N = 1,231 Inside			
Intercept	12.0800	0.0846	<.001
Location 3	0.2188	0.0506	<.001
Bus presence	0.1272	0.0549	.021
Wind speed	–0.1722	0.0679	.012
Wind direction toward shelter, lagged 3 periods	–0.4534	0.1376	<.001
Wind direction with the flow of traffic, lagged 3 periods	–0.4138	0.0933	<.001
Temperature	–0.0336	0.0014	<.001
Vehicle flow: wind speed: wind direction with the flow of traffic	0.0002	0.0001	<.001
N = 1,231 Outside			
Intercept	12.4194	0.0674	<.001
Location 3	0.2454	0.0398	<.001
Bus presence	0.1933	0.0496	<.001
Wind direction with the flow of traffic, lagged 3 periods	–0.3945	0.0769	
Temperature	–0.0469	0.0012	<.001

NOTE: SE = standard error. For N = 1,231 inside, R^2 = .6812 and adjusted R^2 = .6754. For N = 1,231 outside, R^2 = .7895 and adjusted R^2 = .7876.

TABLE 6 Log-Linear $PM_{2.5}$ Regression Model

Variable	Coefficient	SE	*p*
N = 1,231 Inside			
Intercept	3.3350	0.6434	<.001
Location 1	–0.8616	0.0611	<.001
Location 3	–0.7377	0.0377	<.001
Bus presence	0.0632	0.0287	.028
Wind direction toward shelter, lagged 2	–0.1830	0.0700	.009
Temperature	–0.0184	0.0070	.009
Vehicle flow, lagged 2 periods: wind speed, lagged 2 periods: wind direction toward shelter, lagged 2 periods	0.0002	0.0001	<.001
N = 1,015 Outside			
Intercept	1.6820	0.1481	<.001
Location 3	–1.0780	0.0922	<.001
Vehicle flow, lagged 2 periods	0.00005	0.00002	.005
Vehicle flow, lagged 3 periods	0.00005	0.00002	.003
Wind speed, lagged 2 periods	0.0720	0.0292	.014
Humidity	0.0261	0.0040	<.001
Vehicle flow, lagged 2 periods: wind speed, lagged 2 periods: wind direction toward shelter, lagged 2 periods	0.0002	0.0000	<.001

NOTE: For N = 1,231 inside, R^2 = .9547 and adjusted R^2 = .9538. For N = 1,015 outside, R^2 = .8273 and adjusted R^2 = .8225.

$PM_{2.5}$ levels inside the shelter were expected to decrease an average of 20% 2 min after wind blows toward the shelter. $PM_{2.5}$ levels were expected to decrease inside the shelter at Location 1, with Location 2 as the reference. Weather was a consistently significant descriptor in the models. Temperature, relative humidity, or both were significant in every model.

Heavy vehicle flow was not significant in any model. Total vehicle flow, however, was significant in the UFP inside model. Lagged total vehicle flow was significant in the $PM_{2.5}$ outside model. Lagged significance explains the time it takes vehicle-based pollution to reach the shelter from the roadway.

Interactions between wind characteristics and the location dummy variables did not yield significance. UFP concentrations were expected to be lower on average when wind speed at Location 1 increases, and higher on average when wind blows in the direction of traffic at Location 1. Finally, the joint effect of vehicle flow, wind speed, and wind direction was estimated to increase UFP concentrations inside the shelter, $PM_{2.5}$ concentrations inside the shelter, and $PM_{2.5}$ concentrations outside the shelter.

AUTOREGRESSIVE MODEL RESULTS

Following specification of the initial model for each particulate, models were tested for serial correlation, a common occurrence in time series data sets. Time series models are prone to serial correlation because the error term from one time period depends in some systematic way on the value of the error term in other time periods. The classical assumptions of linear regression state that the error terms of successive periods must be uncorrelated. The Durbin–Watson and Ljung–Box Q-statistic were used to test the specified models in Tables 5 and 6; all models had significant positive serial correlation.

In the presence of serial correlation, standard errors tend to be underestimated, which leads to the inclusion of nonsignificant variables in the model. Serial correlation for the models in Tables 5 and 6 was corrected by using an autoregressive model, AR(1). After application of the AR(1) term, insignificant variables were removed and the models rerun until all variables were significant at $\alpha = 0.05$. No interactive or lagged terms were significant. The final model specifications are presented in Tables 7 and 8. Location 3 is statistically significant in all four models. Bus presence and temperature are significant in three models. Of the variables listed in Table 2, only vehicle flow is not significant in any model. The signs of the variables are in line with expectations, according to the literature findings. The coefficients of the models indicate percentage changes in the dependent variable per unit change of the independent variable, all else equal.

Wind speed variables were significant inside the shelter for UFPs and outside the shelter for $PM_{2.5}$. Increased wind speed inside the shelter is expected to lower UFP concentrations, indicating wind is clearing out pollutants that would otherwise collect in the confined space. Wind outside the shelter brings higher $PM_{2.5}$ levels after a 2-min lag period. As temperature rises inside the shelter, lower particulate concentrations are expected. This temperature effect was apparent in substantially different morning and evening particulate concentrations. Although the temperature range observed in this study is narrow, the temperature variable may be acting as a proxy for unspecified variables. Notably, temperature is positively correlated with the time of day (morning versus evening). In addition, temperature can be correlated with other weather-related phenomena, such as changing inversion layers.

TABLE 7 Log-Linear AR(1) UFP Regression Models

Variable	Coefficient	SE	p
N = 445 Inside			
AR(1)	0.7326	0.0328	<.001
Intercept	11.7040	0.1559	<.001
Location 3	0.2603	0.1047	.003
Bus presence	0.0986	0.0336	.001
Wind speed	–0.0663	0.0456	.037
Temperature	–0.0304	0.0030	.000
N = 1,231 Outside			
AR(1)	0.7573	0.0191	<.001
Intercept	12.5268	0.1535	<.001
Location 3	0.2761	0.0676	<.001
Bus presence	0.0544	0.0218	.003
Temperature	–0.0499	0.0030	.003

NOTE: For N = 445 inside, R^2 = .5714 and adjusted R^2 = .5665. For N = 1,231 outside, R^2 = .6303 and adjusted R^2 = .6294.

Significant traffic-related variables in the autoregressive models are limited to bus presence. The routine presence of a diesel engine close to the shelters increases exposure to UFPs and $PM_{2.5}$ for passengers waiting inside the shelter, and outside the shelter for $PM_{2.5}$. An unexpected outcome was the insignificance of all vehicle and heavy-vehicle flow variables in the final AR(1) models, given the considerable body of literature showing higher pollutant levels near roadways, in which vehicles are the primary polluters. It is very likely that the joint effect of lagged vehicle pollution and wind are now captured by the serial correlation term, suggesting the importance of a period t pollution level in explaining the pollution level at period $t + 1$.

Significant location variables were limited to Location 3. Location 3 is close to an intersection with a major four-lane cross street and significant congestion levels; Locations 1 and 2 are close to minor intersections with two-lane cross streets. The sign for this variable is dependent on monitor location and pollutant. Both $PM_{2.5}$ and UFP concentrations are expected to be greater inside the shelter at Location 3, all else equal. Outside the shelter, $PM_{2.5}$ concentrations are expected to be lower at Location 3.

TABLE 8 Log-Linear AR(1) $PM_{2.5}$ Regression Models

Variable	Coefficient	SE	p
N = 1,185 Inside			
AR(1)	0.9524	0.0096	<.001
Intercept	6.0064	0.2476	<.001
Location 3	0.2805	0.1081	.002
Bus presence	0.0320	0.0142	.006
Temperature	–0.0657	0.0044	.000
N = 223 Outside			
AR(1)	0.6851	0.0498	<.001
Intercept	1.8402	0.2480	<.001
Location 3	–1.0516	0.1822	<.001
Wind speed Lag 2	0.0626	0.0234	.002
Relative humidity	0.0263	0.0076	<.001

NOTE: For N = 1,185 inside, R^2 = .8877 and adjusted R^2 = .8873. For N = 223 outside, R^2 = .7209 and adjusted R^2 = .7158.

TABLE 9 Elasticity at the Mean Value of the Independent Variable and Unit Change Values, UFP

Variable	Elasticity	Variable Unit Increase Change (%)
Inside		
Location 3	na	118.5
Bus presence	na	22.9
Wind speed	–0.053	–6.3
Temperature	–1.558	–3.1
Outside		
Bus presence	na	104.6
Temperature	–2.497	–5.0

NOTE: na = not applicable.

Elasticity and the effects of a one-unit increase in independent variables (semielasticity) were calculated from the AR(1) model results, presented in Tables 9 and 10. These values are particularly useful for comparing differences in variable effects inside and outside bus stop shelters. For instance, temperature is less elastic inside the shelter than outside the shelter for UFPs, meaning the shelter is dampening the responsiveness of UFPs to changes in temperature. The same can be seen for the marginal increase, in which a 1° increase in temperature is expected to lead to a 3% and 5% decrease in UFP concentration inside and outside the shelter, respectively.

Aside from temperature, most other independent variables are relatively inelastic; their elasticity ratio is less than one, indicating more unresponsiveness of the dependent variable to changes in the independent variables. Keeping inelasticity in mind, the marginal increase of bus presence for UFP outside the shelter is of note. When the bus is at the shelter, UFP concentrations are expected to rise 105%,

TABLE 10 Elasticity at the Mean Value of the Independent Variable and Unit Change Values, $PM_{2.5}$

Variable	Elasticity	Variable Unit Increase Change (%)
Inside		
Location 3	na	119.3
Bus presence	na	14.5
Temperature	–3.174	–6.4
Outside		
Location 3	na	48.42
Wind speed lag 2	0.053	6.46
Relative humidity	1.133	2.67

NOTE: na = not applicable.

compared with just 23% inside the shelter although, on average, concentrations are higher inside the shelter, which may indicate that the shelter traps and maintains a higher level of particulates on average. The effects of Location 3 are similarly substantial, expecting concentration increases of more than 100% inside the shelter for UFPs and $PM_{2.5}$. The effect of Location 3 is less, although still notable, outside the shelter for $PM_{2.5}$. Location 3 is close to an intersection with a major four-lane cross street and significant congestion levels; Locations 1 and 2 are close to minor intersections with two-lane cross streets.

The AR(1) models suggest local variables such as wind speed and bus presence affect particulates differently inside and outside the shelter. Future research is needed to expand the experimental design and better understand how shelter design can be used to minimize transit users' exposure. The magnitude of variable coefficients may also be used as a metric for minimizing exposure.

CONCLUSIONS

This study uses a log-linear regression model with lagged variables to determine the effects of several categories of environmental influences on exposure in bus stop shelters along busy urban corridors. Understanding how each variable differently affects particulate concentrations inside and outside a shelter is crucial for minimizing exposure for waiting transit passengers. As noted by others, transit agencies do not intend for passengers to be exposed to greater particulate concentrations, although air quality considerations are not included in any known guidelines. An increasing body of research demonstrates differences in particulate concentrations in and around bus stop shelters.

Among the traffic-related variables studied here, bus presence is the most significant and persistent variable. This result highlights the importance of reduced idling at the bus stops to improve air quality for transit riders that remain in the shelter waiting for a bus. Any operational improvement, such as Transit Signal Priority or Automatic Fare Payment, that reduces unnecessary bus idling at bus shelters will improve air quality for transit riders. Meteorological variables (temperature and humidity) also have a significant effect on exposure. Regression results indicate that to reduce unnecessary exposure to PM and UFP pollution it is particularly important to reduce passenger waiting time inside bus shelters on colder days.

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