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Associations of $PM_{2.5}$ and black carbon concentrations with traffic, idling, background pollution, and meteorology during school dismissals

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ABSTRACT

An air quality study was performed outside a cluster of schools in the East Harlem neighborhood of New York City. $PM_{2.5}$ and black carbon concentrations were monitored using real-time equipment with a one-minute averaging interval. Monitoring was performed at 1:45–3:30 PM during school days over the period October 31–November 17, 2006. The designated time period was chosen to capture vehicle emissions during end-of-day dismissals from the schools. During the monitoring period, minute-by-minute volume counts of idling and passing school buses, diesel trucks, and automobiles were obtained. These data were transcribed into time series of number of diesel vehicles idling, number of gasoline automobiles idling, number of diesel vehicles passing, and number of automobiles passing along the block adjacent to the school cluster. Multivariate regression models of the log-transform of $PM_{2.5}$ and black carbon (BC) concentrations in the East Harlem street canyon were developed using the observation data and data from the New York State Department of Environmental Conservation on meteorology and background $PM_{2.5}$. Analysis of variance was used to test the contribution of each covariate to variability in the log-transformed concentrations as a means to judge the relative contribution of each covariate. The models demonstrated that variability in background $PM_{2.5}$ contributes 80.9% of the variability in log[$PM_{2.5}$] and 81.5% of the variability in log[BC]. Local traffic sources were demonstrated to contribute 5.8% of the variability in log[BC] and only 0.43% of the variability in log[$PM_{2.5}$]. Diesel idling and passing were both significant contributors to variability in log[BC], while diesel passing was a significant contributor to log[$PM_{2.5}$]. Automobile idling and passing did not contribute significant levels of variability to either concentration. The remainder of variability in each model was explained by temperature, along-canyon wind, and cross-canyon wind, which were all significant in the models.

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1. Introduction

New York City (NYC) consists of a complex array of buildings and street canyons with tremendous variation in building height, canyon width, and vegetation (Civerolo et al., 2007). Complex building arrangements have been shown to produce heterogeneities in the airflow and turbulence structure at ground level (e.g. Kastner-Klein and Rotach, 2004). Air pollutant concentrations within the urban boundary layer are controlled by a combination of industrial and vehicular sources and meteorological factors. Additionally, differences in fuel type (diesel vs. gasoline) and driving behaviors (idling, cruising, accelerating, and decelerating) can have a significant impact on concentrations at ground level (Namdeo et al., 2002; Corfa et al., 2004; Oxley and ApSimon, 2007; Sharma et al., 2005). All of these factors can lead to spatiotemporal variation in air quality within the urban environment. This variability can reduce the utility of background air quality measurements in epidemiological studies (Wilson et al., 2005).

The spatiotemporal nature of air quality data becomes particularly important when studying acute health effects, such as asthma. Asthma attacks can be triggered almost instantaneously by airborne environmental exposures (Corburn et al., 2006). Documented environmental triggers of asthma include fine particulate matter with a 50% cut-point at an aerodynamic diameter of 2.5 μm ($PM_{2.5}$) (Kappos et al., 2004) and black carbon (BC) (Wichmann et al., 2005; Delfino et al., 2003). BC is a component of particulate matter formed during diesel fuel combustion and is often measured to assess emissions from diesel vehicles (Díaz-Robles et al., in press). Given the potential for brief pollutant exposures to trigger asthma attacks, there is a need to study emissions of asthma precipitators over shorter time periods to learn how to remediate the environment of asthma patients.

In an urban microenvironment, it is possible that close proximity to diesel emitters increases risk of experiencing attacks for asthmatic children. Children are exposed to freshly emitted particulate matter when boarding and riding diesel school buses. Sabin et al. (2005)

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demonstrated BC concentrations inside school buses that were 2–5 times higher than concentrations at bus stops. However, this study was performed in suburban Los Angeles, where lower building density and the associated planetary boundary layer may cause vehicle emissions to disperse more rapidly than in a deep urban canyon. There is a need to describe children's exposures to diesel emissions within the dense urban environment.

The objective of this research was to characterize the air quality and traffic patterns outside a school environment during student dismissal to assess how traffic might be mitigated to improve air quality and decrease absenteeism related to asthma attacks. This study was performed as part of the Asthma Free School Zone project, which works with various New York City schools to reduce preventable causes of asthma in and around the school environment. The study presented here included development of a multivariate model of $PM_{2.5}$ and BC concentrations in a street canyon adjacent to a cluster of school buildings as a function of vehicle type, vehicle behavior, meteorology, and background pollution. Following micro-

Fig. 1. Map of the sampling area. (a) New York City. (b) School cluster around E. 104th Street. Courtesy of Google Maps.

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scale urban air quality studies such as DAPPLE (Colvile et al., 2004), the focus of the study design was to assess the impact of localized, short-time factors such as traffic loads, vehicle behaviors and types, and school dismissal practices on $PM_{2.5}$ and BC concentration. The model then permitted determination of the important traffic-based associations with pollution levels elevated beyond background and identification of features of the dismissal process that might impact children's exposures.

2. Experimental methods

The study was performed in a street canyon adjacent to four schools: The Reece School, Public School (P.S.) 171, Harbor Science and Arts Charter School, and Central Park East II. The canyon was located in the East Harlem neighborhood of NYC on East 104th Street between Fifth and Madison Avenues. This neighborhood was selected because it has the highest prevalence of asthma hospitalizations, 11.9 per 1000 people in 2005, in Manhattan (NYC DOHMH, 2007). The location of the block within NYC is shown in Fig. 1a, and a close-up showing the orientation of the schools and the sampling location is shown in Fig. 1b. School children from The Reece School and P.S. 171 were dismissed into the East 104th Street canyon during the daily observation period. Dismissal for The Reece School occurred at approximately 2:15–2:25 PM each day, and dismissal for P.S. 171 was at approximately 2:45–3:10 PM. A sampling cart containing monitors for $PM_{2.5}$ and BC was positioned at the edge of the fenced-in play area of P.S. 171 at East 104th Street, as shown in Fig. 1b. The sampling cart location was selected to be close to the site where the majority of children gather just prior to end-of-day dismissal of these two schools.

$PM_{2.5}$ was monitored using two SidePak (TSI, Inc. Model AM-510, Shoreview, MN) portable continuous aerosol concentration monitors each fitted with a size-selective nozzle having a 50% cut-point at 2.5 µm. The SidePak measures aerosol concentration through laser photometry. The size of an aerosol particle is related to the intensity of the light scattered as the particle crosses a laser beam. With a fixed airflow and sampling interval set by the user and an assumed particle density of 819 kg/m^3, concentration can be computed in units of mg/m^3. Each SidePak is factory-calibrated using a series of known concentrations of emery oil over the range 0.001–20 mg/m^3. Although this range is large, the calibration curve is linear so that changes in instrument response are expected to reflect true changes in ambient concentration. $PM_{2.5}$ was monitored with a resolution of 1 min for the Asthma Free School Zone study. The reported $PM_{2.5}$ concentrations were adjusted for bias related to relative humidity prior to data analysis (Ramachandran et al., 2003).

An aethalometer (Magee Scientific, Model AE-16, Berkeley, CA) was used for continuous BC monitoring (Hansen et al., 1984). The aethalometer pumps particle-laden air at a set flow rate and collects the particulate matter on a quartz fiber filter tape. A single wavelength infrared light (880 nm) of known intensity is directed onto the collection area. BC on the filter tape absorbs a portion of the light, and the remaining light passes through the filter to be sensed by a photodetector on the opposite side of the filter. The concentration of BC over some time interval is related to the differential light attenuation during that time period and the flow rate of air passing through the collection filter tape. The aethalometer sampled at 1 min intervals. In the field sampling cart, the aethalometer was powered by a car battery attached to an AC-DC signal inverter.

Each piece of equipment was synchronized daily to the National Institute for Standards and Technology atomic clock and checked for appropriate flow rate. The data acquisition period was 1:45–3:29 PM each day. Reportable data were acquired over thirteen school days during October 31–November 17, 2006. This amounted to 1362 data points for concentration.

Volumes of passing and idling vehicles were recorded on separate forms based on visual observation. Volume of passing vehicles was logged on a daily form that contained a separate line for each minute of data acquisition and a count column for number of buses, trucks, and automobiles stopped at a red light, passing through a green light, and parking (for a total of nine columns) on the block of East 104th Street where end-of-day dismissals took place. Buses and trucks larger than pick-ups were assumed to use diesel fuel, as followed by Kinney et al. (2000). Pick-up trucks were grouped with automobiles, all of which were assumed to use gasoline fuel. Tally marks were entered for each vehicle type and passing characteristic during each minute. Idling vehicles were logged on a separate form. On this form, a separate line was available for each idling vehicle. On each line, an option for vehicle type (bus, truck, or automobile) was circled. The start and stop time of idling was recorded for each idling vehicle on each line. After the sampling effort was completed, these observational data were entered into spreadsheets as minute-by-minute counts for idling, stopping at a red light, passing through a green light, and parking for each vehicle type at each minute. Hence, there were 1362 data points for each observation variable considered. This count methodology differed from techniques used by Ntziachristos et al. (2007), Carslaw et al. (2007), or Kinney et al. (2000). Kinney et al. (2000) used electronic counters that tallied traffic by fuel type every 15 min for a duration of 8 h and then averaged the count over 8 h. Similarly, Carslaw et al. (2007) used an electronic counter to take 15-minute averages of traffic count and vehicle speed. Ntziachristos et al. (2007) used manual and videotaped counts and sampled at random during 1 min out of every five.

Background data were obtained from the New York State Department of Environmental Conservation (NYS DEC) Air Monitoring website. Hourly data were available for $PM_{2.5}$ concentration (ng/m^3) (Rupprecht & Patashnick, TEOM 1400ab or 2025 Partisol, East Greenbush, NY), wind speed (mph) (MetOne, Sonic Anemometer, Grants Pass, OR; or, Climatronics, Sonic Anemometer, Bohemia, NY), wind direction (degrees) (MetOne, Sonic Anemometer, Grants Pass, OR; or, Climatronics, Sonic Anemometer, Bohemia, NY), temperature (°F) (Teledyne Corp., Geotech Model T-200, Thousand Oaks, CA; Bristol Corp., Model 9Q6, Waterbury, CT; Climatronics, P/N 100826, Bohemia, NY), relative humidity (%) (Teledyne Corp., Geotech Model RH200 Helical Hydroscope LVDT, Thousand Oaks, CA), and barometric pressure (in Hg) (Teledyne Corp., Geotech Model BP300 Capsular — LVDT, Thousand Oaks, CA). Average daily values for each of these variables are provided in Table 1. Because the data were reported hourly, only thirty-nine unique data points were used for each meteorological variable. To generate a one-minute dataset, the background $PM_{2.5}$ and meteorology values were repeated and paired with each one-minute ground-level concentration observation made within that hour. Unfortunately, there were no available background concentration data for BC. Data were obtained by the NYS DEC at several sites

Table 1
Average meteorological conditions for each daily sampling period (1:45–3:29)

Date	Temp. (°C)	Wind speed (m/s)	Wind direction (degrees)	Relative humidity (%)	Barometric pressure (mm Hg)
10/31/2006	20	7.4	216 (SSW)	56	756
11/1/2006	21	5.0	241 (WSW)	61	758
11/2/2006	12	5.8	261 (W)	53	759
11/3/2006	9	6.3	238 (WSW)	45	766
11/6/2006	14	5.2	219 (SSW)	43	769
11/7/2006	14	5.9	147 (SSE)	85	764
11/9/2006	20	7.3	283 (W)	68	749
11/10/2006	16	5.1	282 (W)	54	759
11/13/2006	16	10.6	62 (ENE)	94	756
11/14/2006	16	5.8	254 (WSW)	86	754
11/15/2006	16	4.5	118 (ESE)	95	759
11/16/2006	19	14.4	167 (S)	93	752
11/17/2006	16	9.7	281 (W)	61	754

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Table 2
Dismissal times, average $PM_{2.5}$ and BC concentrations, and peak $PM_{2.5}$ and BC concentrations for each school with *p*-values for the Student *t*-test for significant differences

	Dismissal duration (min)		Avg. $PM_{2.5}$ conc. (μg/m^3)		Avg. BC conc. (μg/m^3)		Peak $PM_{2.5}$ conc. (μg/m^3)		Peak BC conc. (μg/m^3)	
	Reece	PS 171	Reece	PS 171	Reece	PS 171	Reece	PS 171	Reece	PS 171
10/31/2006	11	28	48.1	47.8	2.5	2.8	57.0	62.0	3.4	5.0
11/1/2006	15	35	42.9	47.7	2.4	2.1	51.5	103.0	5.4	7.3
11/2/2006	*15*	27	22.3	20.1	1.1	1.2	26.5	24.5	2.4	2.2
11/3/2006	*14*	44	11.0	22.6	1.8	1.5	19.0	150.5	6.9	8.4
11/6/2006	13	27	55.5	51.7	2.3	2.5	76.0	70.0	4.8	7.2
11/7/2006	10	n/a	11.3	n/a	1.1	n/a	16.5	n/a	1.6	n/a
11/9/2006	*13*	26	13.8	15.1	1.8	1.9	18.5	27.0	6.1	4.8
11/10/2006	*17*	34	7.0	6.5	1.4	1.4	9.0	20.0	3.6	2.9
11/13/2006	10	37	29.8	29.3	1.4	1.3	34.5	35.0	1.5	3.2
11/14/2006	11	30	19.5	16.6	2.4	2.4	23.0	24.5	4.2	4.3
11/15/2006	10	22	63.4	72.7	1.9	3.4	67.0	84.5	2.5	4.8
11/16/2006	13	32	23.7	22.6	0.8	0.9	31.5	34.5	1.0	1.4
11/17/2006	11	45	8.5	8.1	1.8	1.5	11.5	33.5	5.8	7.0
Average	12	32	27.5	30.1	1.8	1.9	34.0	55.8	3.8	4.9
St. Dev.	2	7	19.0	20.4	0.6	0.8	21.9	40.1	1.9	2.2
p-value	$\ll$0.001		0.44		0.36		0.072		0.14	

Note that the *t*-test excluded 11/7 because no data were obtained for P.S. 171 for that day.

throughout NYC. These data were averaged over all monitoring sites to arrive at an average background level for each parameter.

3. Statistical methods

Analysis began with a comparison between summary statistics from The Reece School and P.S. 171 end-of-day dismissals. The Student *t*-test was applied to dismissal duration, average $PM_{2.5}$ concentration, average BC concentration, maximum $PM_{2.5}$ concentration, and maximum BC concentration for all sampling days. The hypothesis employed was no difference between the end-of-day dismissals for each of the two schools with respect to each parameter. The objective of these tests was to determine whether or not traffic associated with the schools' dismissal had an impact on airborne concentrations.

The next comparison was performed to determine if the measured $PM_{2.5}$ concentrations were significantly different from background levels across NYC. As for the schools comparison, measured and background $PM_{2.5}$ concentrations were compared for each day to determine if they were significantly different. The Student *t*-test was applied for all SidePak samplers and all DEC monitors on each day, with the null hypothesis indicating no difference between measured and background $PM_{2.5}$ concentrations despite variation in monitoring unit, space, and time. If the null hypothesis were supported, this would demonstrate that the measured $PM_{2.5}$ concentrations at the monitoring site were not different from background $PM_{2.5}$ as a function of both inter-sampler variability and temporal variability. However, this was not the case, as presented below in the Results section. A similar test for BC would have been desirable, but data for background BC were not available.

The primary statistical analysis was development of a generalized linear model (GLM) for $PM_{2.5}$ and BC concentrations at any given time. Westmoreland et al. (2007) and Carslaw et al. (2007) used similar multivariate approaches to examine pollutant concentration as a function of dependent variables:

$$\log C = \beta_0 + \beta_1 Idle_{\mathrm{BusTruck}} + \beta_2 Idle_{\mathrm{Car}} + \beta_3 Pass_{\mathrm{BusTruck}} + \beta_4 Pass_{\mathrm{Car}} + \beta_5 Temp + \beta_6 U + \beta_7 V + \varepsilon \qquad (1)$$

where C = concentration (of either $PM_{2.5}$ or BC), β_i = regression coefficients, $Idle_j$ = number of idling vehicles per minute (j = buses and trucks or cars), $Pass_j$ = number of passing vehicles per minute, $Temp$ = ambient temperature, U = along street wind index, V = cross-street wind index, and ε = residuals. Following Carslaw et al. (2007), Westmoreland et al. (2007), and Chaloulakou et al. (2003), the wind indices accounted for interactions between wind speed (*WS*) and wind direction θ (rad): $U = WS\cos(\varphi - \theta)$ and $V = WS\sin(\varphi - \theta)$, where φ = azimuth of the block (2.44 rad). A logarithmic function of concentration was used in the model both to improve normality of the input data and to account for nonlinear trends in the independent variables. Use of the logarithmic function also acted to reduce the impact of any outliers in the concentration that could skew the regression results. Time lags were not employed in the regression because the one-minute resolution was assumed sufficient for transport across the canyon for the purpose of this study. The regression was run using the R Software Package, which is an open source statistical computing language available for free on the internet (R Foundation for Statistical Computing, v. 2.2.0, Vienna, Austria). The regression was performed using the GLM function, and the model fit was achieved by an iteratively weighted least squares algorithm. This process was performed for log [$PM_{2.5}$] and log [BC] data for all days combined during the 1:45–3:29 PM sampling period with 1362 data points in each regression. Significance of each independent model coefficient of the regressions was determined using the Student *t*-test, contribution of the variability of each covariate to the overall variability in log[$PM_{2.5}$] and log[BC] was determined using analysis of variance, and overall significance of the relationship between dependent and independent variables was established with the *F*-test. Goodness of fit was also presented using the R^2 and adjusted R^2 coefficients of determination.

Interdependency between variables was tested prior to formulating the final models. Idling and passing were broken down by fuel type (assumed diesel for buses and trucks, gasoline for automobiles) in the model because regression of idling as a function of passing showed very low coefficient of determination (buses and trucks: R^2 = 0.073, adj R^2 = 0.072; automobiles: $R^2 = 3.9 \times 10^{-4}$, adj $R^2 = -3.4 \times 10^{-4}$) so that idling and passing were deemed independent of each other. Likewise, regression of bus and truck observations as a function of automobile observations yielded low coefficient of determination (R^2 = 0.038, adj R^2 = 0.038). Barometric pressure and relative humidity were not included in the final models because they are both functions of temperature. Hence the final model included idling and passing by fuel type (diesel buses and trucks, gasoline automobiles), temperature, and the along-street and cross-street components of wind.

4. Results

Table 2 shows the comparison of the average characteristics of the end-of-day dismissals at The Reece School and P.S. 171. Note that no data are provided for P.S. 171 on November 7, 2006 because the school

Table 3
Average and standard deviation of measured and background $PM_{2.5}$ concentrations (ng/m^3) for each daily sampling period (1:45–3:29), and *p*-values for the Student *t*-test for significant differences

Date	E. 104th		Background		*p*-value
	Average	St. Dev.	Average	St. Dev.	
10/31/2006	49 245	5849	19 367	865	$\ll$0.001
11/1/2006	44 873	7302	14 094	1107	$\ll$0.001
11/2/2006	20 769	2550	8237	18	$\ll$0.001
11/3/2006	15 864	13 934	5007	126	$\ll$0.001
11/6/2006	52 143	5411	18 377	1875	$\ll$0.001
11/7/2006	11 689	1227	9022	184	$\ll$0.001
11/9/2006	15 146	1874	6880	750	$\ll$0.001
11/10/2006	6519	1653	7501	984	$\ll$0.001
11/13/2006	30 108	1355	10 099	62	$\ll$0.001
11/14/2006	19 075	5992	9558	1256	$\ll$0.001
11/15/2006	69 899	7702	18 047	27	$\ll$0.001
11/16/2006	22 328	2122	10 032	310	$\ll$0.001
11/17/2006	8177	2223	7822	759	0.066

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Table 4
Traffic volume counts by fuel type and vehicle behavior (idling or passing) for each daily sampling period and for all days

Date	Idling		Passing	
	Diesel	Gasoline	Diesel	Gasoline
10/31/2006	60	117	158	152
11/1/2006	73	52	99	162
11/2/2006	85	201	244	193
11/3/2006	138	287	334	169
11/6/2006	109	156	219	130
11/7/2006	10	60	84	146
11/9/2006	55	148	187	133
11/10/2006	73	173	207	157
11/13/2006	45	88	125	134
11/14/2006	76	154	204	154
11/15/2006	81	79	120	134
11/16/2006	83	146	192	244
11/17/2006	93	121	165	143
Average	75.5	137.1	179.8	157.8
St. Dev.	30.8	63.5	67.0	31.3
p-value (diesel vs. gasoline)	5.9×10^{-3}		0.30	
p-value (idling vs. passing)	1.7×10^{-4}			

Note that November 7, 2006 is excluded from overall statistics because it was a holiday for New York City Public Schools (Election Day).

was closed for Election Day. The only highly significant difference between the two monitoring events was the duration of the dismissal, which averaged 32 min for P.S. 171 and only 12 min for The Reece School. Peak values of $PM_{2.5}$ concentration were nearly significantly different, with a *p*-value of 0.072. Measured average BC concentration was 6.4% of the measured average $PM_{2.5}$ concentration, based on the pooled data from each school. For peak concentration, this percentage increased to 9.6% but was more uncertain because the difference between pooled peak $PM_{2.5}$ concentrations was larger for the two schools' end-of-day dismissals.

Table 3 displays the average and standard deviation of the measured $PM_{2.5}$ concentrations for each sampling day during the 1:45–3:29 PM sampling and observation period and background $PM_{2.5}$ levels reported by the NYS DEC. Highly significant differences (p-value $\ll 0.001$) between the measured and background levels were observed on twelve of the thirteen days when data were reported. For all but one of these days, measured $PM_{2.5}$ concentration was 29.6–287.3% higher than background levels. Large eddy simulation modeling studies have shown that concentrations within street canyons with aspect ratios ranging from 0.5–2 can reach roughly ten times concentrations at rooftop levels when the freestream wind is perpendicular to the street in idealized studies (Liu et al., 2005; So et al., 2005) and 175% of rooftop (in this case measured at 20 m with a 5 m “ground level” representation) when the freestream wind is parallel to the street in which samples were obtained in a simulation of a point release in Baltimore (Tseng et al., 2006). On November 17, 2006, the measured $PM_{2.5}$ concentration was only 4.5% higher than background (p-value = 0.065), and on November 10, 2006, the measured $PM_{2.5}$ concentration was 13.1% lower than the background concentration (p-value $\ll 0.001$). When the data from November 10 and 17 were removed from the multivariate regression analysis, the significant covariates and their coefficients did not change appreciably. For this reason, these two days were kept in the analysis presented here.

Table 5
Regression coefficients, mean squared errors, *p*-values for *F*-tests of each coefficient, *F*-statistic and *p*-value for *F*-test of the overall model, R^2, and adjusted R^2 instantaneous log[$PM_{2.5}$] for all daily sampling periods (1:45–3:29)

Variables	Estimated coefficient	Mean squared error	*p* (>|*F*|)
(Intercept)	*3.54*	–	–
Number of buses and trucks idling	2.11×10^{-3}	0.082	0.19
Number of cars idling	1.36×10^{-2}	0.099	0.16
Number of buses and trucks passing	8.56×10^{-4}	*0.24*	*0.027*
Number of cars passing	2.30×10^{-3}	0.039	0.37
Background $PM_{2.5}$ conc. (ng/m^3)	6.03×10^{-5}	*86.34*	$\ll 0.001$
Temperature (°F)	-3.76×10^{-3}	*0.68*	<0.001
U (along-street wind)	-1.54×10^{-2}	*11.02*	$\ll 0.001$
V (cross-street wind)	-1.76×10^{-2}	*8.16*	$\ll 0.001$
F-statistic	273.7		
p (>|*F*|)	$\ll 0.001$		
R^2	0.62		
Adj R^2	0.62		

Significant variables are italicized.

Table 6
Regression coefficients, mean squared errors, *p*-values for *F*-tests of each coefficient, *F*-statistic and *p*-value for *F*-test of the overall model, R^2, and adjusted R^2 instantaneous log[BC] for all daily sampling periods (1:45–3:29)

Variables	Estimated coefficient	Mean squared error	*p* (>|*F*|)
(Intercept)	*5.35*	–	–
Number of buses and trucks idling	7.60×10^{-2}	*8.23*	$\ll 0.001$
Number of cars idling	1.98×10^{-2}	0.33	0.20
Number of buses and trucks passing	2.25×10^{-2}	*2.69*	<0.001
Number of cars passing	1.23×10^{-2}	0.01	0.77
Background $PM_{2.5}$ conc. (ng/m^3)	7.34×10^{-5}	*157.76*	$\ll 0.001$
Temperature (°F)	1.61×10^{-2}	*6.83*	$\ll 0.001$
U	-2.29×10^{-2}	*14.60*	$\ll 0.001$
V	1.07×10^{-2}	*3.04*	<0.001
F-statistic	121.2		
p (>|*F*|)	$\ll 0.001$		
R^2	0.42		
Adj R^2	0.41		

Significant variables are italicized.

Table 4 shows the average traffic volume counts by fuel type and behavior (idling or passing) for each test day. On average, 80.9 diesel vehicles and 143.5 gasoline vehicles idled during the 1 h 45 min sampling period, while 187.8 diesel vehicles and 158.8 gasoline vehicles passed along the study block during the same period. A two-tailed Student *t*-test of idling vs. passing for diesel-fueled vehicles showed a highly significant difference (p-value $\ll 0.001$). However, a *t*-test comparing gasoline idling to passing did not yield a significant difference (p-value = 0.46). When comparing idling between diesel and gas-fueled vehicles, there was a significant difference (p-value = 5.6×10^{-3}), but no difference was seen when comparing passing between diesel and gas-fueled vehicles (p-value = 0.18).

Tables 5 and 6 present the coefficients of the independent variables mean squared errors, *F*-test statistics for each variable and the

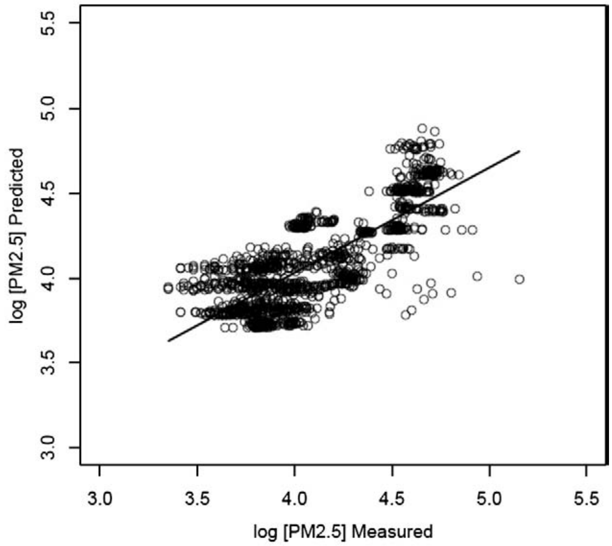

Fig. 2. Log–log transformed predicted $PM_{2.5}$ concentration (ng/m^3) vs. measured $PM_{2.5}$ concentration for all daily sampling periods (1:45–3:29).

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regression model as a whole, respectively, and R^2 and adjusted R^2 coefficient of determination values for the multivariate regressions of log[$PM_{2.5}$] and log[BC] during the monitoring periods. Figs. 2 and 3 plot the accompanying multivariate regressions of the significant variables. An increasing trend between the measured and predicted log-transformed concentration is apparent in each of these plots. For both the log[$PM_{2.5}$] and log[BC] models, *F*-test statistics demonstrate that the relationship between the log-transformed concentrations and the set of independent variables is highly significant (p-value$\ll 0.001$). However, the goodness of fit is much better for log[$PM_{2.5}$] ($R^2=0.62$, adjusted $R^2=0.62$) than for log[BC] ($R^2=0.41$, adjusted $R^2=0.41$).

Among the traffic-count data predicting log-transformed concentration, the number of buses and trucks idling at any given time was a highly significant predictor of log [BC] (p-value$\ll 0.001$). Bus and truck idling was not significant in the log[$PM_{2.5}$] regression (p-value$=0.19$). The number of buses and trucks passing along East 104th Street was a significant predictor of both log[BC] (p-value<0.001) and log[$PM_{2.5}$] (p-value$=0.027$). The BC results agree with Kinney et al.'s (2000) findings where there was a significant increase in average local elemental carbon concentration as a function of increased local eight-hour counts of diesel vehicle counts, but in Kinney's work, local $PM_{2.5}$ concentration did not increase markedly as a function of local diesel vehicle count. The contribution of bus and truck idling to log[BC] was significantly higher than was car idling, which is consistent with Sabin et al.'s (2005) finding that diesel engines produce markedly higher concentrations of BC than gasoline engines among school bus fleets. The number of automobiles idling was not a significant predictor of log[BC] (p-value$=0.20$) or log [$PM_{2.5}$] (p-value$=0.16$). Likewise, the number of cars passing was not a significant predictor of either log[BC] (p-value$=0.77$) or log[$PM_{2.5}$] (p-value$=0.37$).

Background $PM_{2.5}$ concentration was shown to be the most significant predictor of street-level log[$PM_{2.5}$] and log[BC] (p-value$\ll 0.001$ in both cases). The log-transform of measured $PM_{2.5}$ and BC varied positively with background $PM_{2.5}$ concentration. Wilson et al. (2005) reviewed several intraurban field studies and demonstrated that, for short-time resolved studies, there is generally good correlation among multiple measurement sites so that a relationship to background is not surprising. Among the meteorological variables tested, the along-street (U) and cross-street (V) components of wind and temperature were highly significant predictors of both log[$PM_{2.5}$] (U: p-value$\ll 0.001$; V: p-value$\ll 0.001$; Temp: p-value<0.001) and log[BC] (U: p-value$\ll 0.001$; V: p-value<0.001; Temp: p-value$\ll 0.001$). log[$PM_{2.5}$] varied negatively with each of the meteorological variables, while log[BC] increased with increasing temperature and V and decreased with increasing U. Kukkonen et al. (2003) have used measured data and the Operational Street Pollution Model (OSPM) to demonstrate that contaminant concentration tends to increase with decreasing wind speed. Carslaw et al. (2007) also demonstrated a tendency for increased log[NO_x] as each component of wind speed approaches zero and with decreasing temperature. It is unclear why an increase in the cross-canyon wind would ventilate $PM_{2.5}$ from the canyon but cause retention of BC.

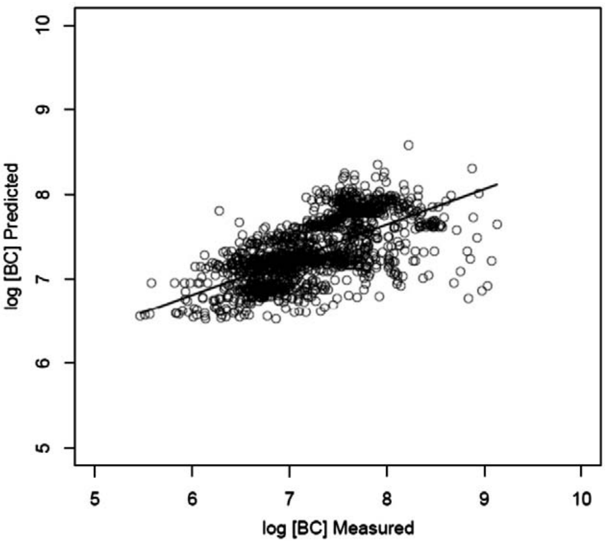

Fig. 3. Log–log transformed predicted black carbon concentration (ng/m^3) vs. measured black carbon concentration for all daily sampling periods (1:45–3:29).

5. Discussion

The factors examined during this analysis can be broken into several categories, including school dismissal practices, vehicle fuel type, vehicular idling, traffic volume, background air quality, and meteorology. The first four categories are influential at the localized spatial and temporal levels, while background air quality and meteorology have metropolitan and regional impacts. The influence of the multi-scale dynamic urban environment has been recognized for several years and contributes insight into the process of improving air quality at multiple levels (Oxley and ApSimon, 2007).

End-of-day dismissal practices for either school were not shown to have a significant impact on exposure at any given time. The average and peak values for $PM_{2.5}$ and BC concentration were not significantly different for The Reece School and P.S. 171, as shown in Table 2. The largest significant difference between the two subsets was in the dismissal time, where the P.S. 171 dismissal was 2.67 times longer than that for The Reece School. With students from P.S. 171 waiting in the school yard for their buses or parents to arrive, this difference implies that their doses of $PM_{2.5}$ and BC were also larger. In part, the disparity in dismissal times is likely related to the difference in size of the student body between The Reece School, which has less than 75 students, and P.S. 171, which has roughly 550 students. Idling for any given bus was rarely more than a minute for The Reece School. Longer idling times were recorded for buses and trucks during the P.S. 171 dismissal.

The overall regression models were highly significant for both log [$PM_{2.5}$] and log[BC], with overall *F*-test yielding a p-value$\ll 0.001$. Review of the mean squared errors shows that 80.9% and 81.5% of the variance in log[$PM_{2.5}$] and log[BC], respectively is due to background $PM_{2.5}$ concentration. Even with this strong influence of background $PM_{2.5}$, the remaining covariates in the model are highly significant, with partial *F*-tests producing p-value$\ll 0.001$ for log[$PM_{2.5}$] and log[BC]. These covariates can be analyzed to discern the relative importance of local traffic behaviors, fuel type, and meteorology.

Local traffic-related sources are much more important for log[BC] than log[$PM_{2.5}$], with all idling and passing traffic accounting for 5.8% of the variability in log[BC] and only 0.43% accounting for the variability in log[$PM_{2.5}$]. Diesel emissions comprised 96.9% of the variability in log[BC] and 69.9% of the variability in log[$PM_{2.5}$] related to local traffic. Seventy-three percent of the traffic-related variability in log[BC] was due to diesel idling while 23.9% was due to diesel passing. Automobile idling made the next largest contribution to traffic-related variability at 2.93%, and automobile passing contributed less than 1% of traffic-related variability in log[BC]. For log[$PM_{2.5}$], diesel passing contributed 52.0% of the traffic-related variability, diesel idling contributed 17.9%, automobile idling contributed 21.6%, and automobile passing contributed 8.5% of the traffic-related variability. However, the latter three sources were so small that only variability in the diesel passing covariate produced a significant change in variability of log[$PM_{2.5}$]. These findings suggest that the presence of diesel-burning vehicles can have a significant impact on short-term airborne concentrations and that, for BC, diesel idling can be an important cause of localized concentrations. This result is not surprising because it is well known that BC is a component of diesel

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combustion particulate emissions based on chemical analyses and source apportionment field studies (Grose et al., 2006; Díaz-Robles et al., in press; Maciejczyk et al., 2004). However, this finding does further highlight the important contribution of diesel vehicles, in particular school buses, to this problem. Furthermore, a primary goal of the Asthma Free School Zone project is to reduce unnecessary pollution source contributions near schools. School buses comprised 99.6% of idling diesel vehicles and 88.3% of passing diesel vehicles. Hence, an educational program directed at school bus idling and redirecting some bus traffic can potentially result in small but measurable improvements in BC concentration in the vicinity of the school cluster.

Meteorological factors are important contributors to dispersion patterns in urban environments (Newsome et al., 2005) and were all significant in the multiple regression models developed here. Variability in the along-canyon wind explained 7.5% and 10.3%, respectively, of the variability in log[BC] and log[$PM_{2.5}$]. Given that the regression coefficients for along-canyon wind were negative, it can be inferred that wind-driven ventilation of the canyon provides an important control on airborne concentrations. Variability in the cross-canyon wind explained 1.6% and 7.7% of log[BC] and log[$PM_{2.5}$] respectively. The sign of the regression coefficient was positive for the log[BC] model but negative for the log[$PM_{2.5}$] model. Likewise, variability in temperature explained 3.5% of log[BC] and only 0.64% of log[$PM_{2.5}$] with positive slope in the log[BC] model and negative slope in the log[$PM_{2.5}$] model. The discrepancies in the impact of variability in cross-canyon wind and temperature on variability in concentration make it difficult to interpret the significance of these two factors. Hence, more work is needed to elucidate the significance of cross-canyon winds and ambient temperature on airborne concentrations of BC and $PM_{2.5}$.

Although the focus of this study is on traffic behaviors, background $PM_{2.5}$ and meteorological variables were factored into the study to develop a holistic picture of contributions to air quality. The significance of background $PM_{2.5}$ in each of the models affirmed the contribution of regional pollution sources, such as industry. The high significance level of the overall *F*-tests of the models suggests that the set of independent variables was fairly sufficient for describing the measured real-time $PM_{2.5}$ and BC concentration. However, it is likely that some important variables were overlooked or not measured as a result of equipment limitations. Elemental carbon is fairly stable, but in the first minutes after combustion occurs, the BC absorbs more ultraviolet than infrared light (Husain et al., 2007). Because the aethalometer used here measures in the infrared part of the spectrum, a time-lag of the traffic variables may have improved the model fits. Likewise, availability of data from the ultraviolet spectrum superimposed over the infrared one may have enhanced model fit. Corresponding data regarding cold-start emissions would also enhance the model. There were no available metropolitan-wide BC concentration data. It is possible that the fit to the log[BC] data could have been improved if this important parameter were included.

An additional limitation was that measurements of particle number concentration of submicrometer particles were not included based on equipment availability. In a review of PM emitted from motor vehicles, Morawska et al. (2008) stated that emissions from diesel vehicles range in size from 20 to 130 nm, while gasoline engine emissions are typically 20 to 60 nm in diameter with roughly 90% of the particle number concentration comprised of particles smaller than 100 nm. Likewise, in a street canyon in Cambridge, UK, Kumar et al. (2008) found that accumulation mode particles between 300 nm and 2.7 µm comprised only 0.5% of the particle number concentration. However, Zhang et al. (2004) estimated that 87% of the urban particle mass concentration is from particles larger than 100 nm and Shi et al. (2001) estimated that 82% of particle mass concentration was from particles in the size range of 100 nm to 2.8 µm. The results of this study showed that variability in local traffic sources explained only 0.43% of the log[$PM_{2.5}$] model results. Use of particle number concentration as a dependent variable may have increased the model's sensitivity to local traffic sources, as observed for the log[BC] model.

6. Conclusions

Multivariate regression for measured $PM_{2.5}$ and BC concentration data was performed against real-time street-level observations and city-wide background $PM_{2.5}$ concentration and meteorological data. This work is novel because it incorporates time-resolved observations to ascertain the short-term impact of vehicular traffic and idling on concentration levels within an urban street canyon. Detailed information in the traffic observations allows for conclusions to be drawn about the specific causes of elevated $PM_{2.5}$ and BC concentration at a given time. This detailed information, broken down by fuel type (given that trucks and school buses are fueled by diesel) and vehicle behavior (idling or passing) can be used to inform specific policies and enforcement practices related to traffic along urban street canyons, especially when adjacent to vulnerable environments, such as schools. Furthermore, incorporation of meteorological effects (wind speed and direction, relative humidity, barometric pressure) and background $PM_{2.5}$ levels permits removal of potential confounders of the measured concentration so that the impact of traffic and idling can be more fully understood. Using this approach, it was demonstrated that diesel idling and traffic are both significant predictors of real-time ground-level concentrations of BC and diesel traffic is a significant predictor of ground-level $PM_{2.5}$ concentration at the study site.

This technique of applying real-time observations with concentration data is demonstrated here for the school environment. It may also prove to be a useful technique for determining the limits of a policy-based remediation approach in locations where environmental stressors, such as highways or industrial facilities, may swamp any localized traffic effects. Additional analyses are planned to add seasonal effects to this study and, following administration of an environmental education program to curtail idling and traffic, to repeat the multivariate analysis in the East Harlem neighborhood under study for the purpose of determining if environmental education efforts actually decrease the contribution of vehicular traffic and idling to street canyon pollution near the school cluster.

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