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Personal exposures to traffic-related particle pollution among children with asthma in the South Bronx, NY

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Personal exposures to fine particulate matter air pollution ($PM_{2.5}$), and to its traffic-related fraction, were investigated in a group of urban children with asthma. The relationships of personal and outdoor school-site measurements of $PM_{2.5}$ and elemental carbon (EC) were characterized for a total of 40 fifth-grade children. These students, from four South Bronx, NY schools, each carried air pollution monitoring equipment with them for 24 h per day for $\sim$1 month. Daily EC concentrations were estimated using locally calibrated reflectance of the $PM_{2.5}$ samples. Personal EC concentration was more closely related to outdoor school-site EC (median subject-specific: $r = 0.64$) than was personal $PM_{2.5}$ to school-site $PM_{2.5}$ concentration (median subject-specific: $r = 0.33$). Regression models also showed a stronger, more robust association of school site with personal measurements for EC than those for $PM_{2.5}$. High traffic pollution exposure was found to coincide with the weekday early morning rush hour, with higher personal exposures for participants living closer to a highway (<500 ft). A significant linear relationship of home distance from a highway with personal EC pollution exposure was also found (up to 1000 ft). This supports the assumptions by previous epidemiological studies using distance from a highway as an index of traffic PM exposure. These results are also consistent with the assumption that traffic, and especially smoke emitted from diesel vehicles, is a significant contributor to personal PM exposure levels in children living in urban areas such as the South Bronx, NY.
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Introduction

Assessing the impact of localized traffic pollution personal exposure is critical in light of the various health effects that have been found to be associated with proximity to highways (Wjst et al., 1993; Edwards et al., 1994; Duhme et al., 1996; Brunekreef et al., 1997; Kim and Hopke, 2004; McConnell et al., 2006). Several proximity studies have particularly linked traffic exposure to adverse respiratory health effects (Wjst et al., 1993; English et al., 1999; Nicolai et al., 2003; Bayer-Oglesby et al., 2006). Traffic-related air pollution studies showing health effect associations have mainly relied on modeled exposure variables using traffic density metrics or geographic information systems (GIS)-based methods (English et al., 1999; Zmirou et al., 2004; McConnell et al., 2006; Maynard et al., 2007). Other studies have used central-site measurements, or emissions inventories in combination with modeled or empirical traffic exposure indicators (Brauer et al., 2002; Gehring et al., 2002; Hoek et al., 2002; Gauderman et al., 2005; Nordling et al., 2008), including land use regression models (Suglia et al., 2008). Few health studies have measured personal exposure to traffic particles directly (Jansen et al., 2005; Delfino et al., 2006, 2008).

Previous studies have indicated that traffic-generated particulate matter air pollution ($PM_{2.5}$) can appreciably influence both personal and indoor pollutant levels. For example, traffic density was identified as a significant predictor of personal $PM_{2.5}$ levels in a comparison of urban and suburban concentrations in Finland (Koistinen et al., 2001). Traffic was also an important determinant of personal absorbance in Amsterdam and Helsinki (Lanki et al., 2007), and in Barcelona (Jacquemin et al., 2007). In the United States, where diesel vehicles are more limited to truck traffic, in Boston, MA, indoor elemental carbon (EC) levels were associated with distance from a truck route (Baxter et al., 2007), and in Detroit, MI, diesel traffic on the Ambassador Bridge was found to contribute significantly to indoor EC levels of homes in that area (Baxter et al., 2008). These findings suggest that localized diesel pollution could be a major contributor to personal exposure in populations living adjacent to highways and

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truck routes, even if they spend the majority of their time indoors.

Although EC measurements are not unique markers for diesel particle exposure in all cases, previous published findings indicate that EC variation is a reliable indicator of traffic-generated pollution in high-traffic center city areas. In Boston, for example, indoor EC concentrations were linked to local traffic, where total $PM_{2.5}$ was not (Baxter et al., 2007). Levels of both $PM_{2.5}$ and reflectance "black soot" were correlated with increasing truck traffic density and proximity to a roadway (Janssen et al., 2001; Lena et al., 2002). Although site-to-site variation in $PM_{2.5}$ concentrations were modest in Harlem (an NYC community with high rates of asthma and traffic volumes), EC concentrations varied fourfold across sites and were associated with bus and truck counts on adjacent streets (Kinney et al., 2000).

A previous study by New York University (NYU) in the South Bronx area, including ground-level air quality monitoring at various South Bronx sites (2001–2003), also suggests EC to be from traffic in this particular locale (Maciejczyk et al., 2004). Maciejczyk et al. compared South Bronx ground-level concentrations and rooftop monitors at PS154 with those measured at Hunter College on E. 25th street in Manhattan, and found significantly higher concentrations for black carbon (BC) at the South Bronx ground-level sampling sites. The authors report a traffic origin of the BC, as they found lower weekend and higher weekday concentrations. Variations in ground-level BC concentrations in the South Bronx were also shown to be related to local truck traffic density, and were particularly elevated in Hunts Point (Lena et al., 2002), indicating that even within the South Bronx area relative "hotspots" for certain components of particle pollution exist. BC concentrations were also found to be directly correlated with local truck traffic spatial and temporal patterns.

NYU's community-based panel study in the South Bronx, NY, was borne partly from a concern by local residents regarding the potential health effects from exposure to traffic-generated pollution in the area. The highways that encircle the South Bronx—a mixed-use urban community comprises industry, commercial enterprises and residences—are a potentially significant source of particle pollution in the area. By collecting personal and outdoor school-site $PM_{2.5}$ pollution measurements, and using reflectance techniques to estimate concentrations of EC, an important component of diesel exhaust particles, this study seeks to determine the exposure impact of a local source of fine PM pollution (i.e., diesel truck traffic) on a group of urban children with asthma. This study has the advantage of collecting personal measurements of a traffic-related component of the $PM_{2.5}$ in a high-density urban area. The personal monitoring results will also provide further insight into the validity of past studies that used central-monitoring data and distance from roadway metrics as proxies for personal exposures to traffic-generated pollution. Health effects associated with these exposures are reported elsewhere (Spira-Cohen et al., 2009).

Methods

Personal and outdoor school-site air pollution samples were collected at four South Bronx schools during field campaigns in Spring 2002, Spring 2004, Fall 2004 and Spring 2005, respectively. Ten fifth-grade children with asthma were recruited to participate in the study at each school, for a total of 40 children. The participants were followed for ~ 1 month each, during which time they went about their normal school-year activities while also pulling a rolling backpack containing air pollution monitoring equipment. Two of the schools that participated were located immediately adjacent to Interstate highways (<200 ft), and two schools were located several city blocks distant from these highways (>1000 ft) (Figure 1), providing a range of traffic pollution exposures.

On every weekday of the study, participants visited on-site NYU researchers twice daily to change air sampling filters and download motion sensor (Hobo, Onset, Bourne, ME) data. In the case of absence, the students were contacted by the study coordinator to collect the information. Participants were instructed to keep the backpack near them at all times. If the motion sensor data indicated that the child did not carry the bag, then this was recorded in the sampling log and the exposure data was excluded from the analyses. Time–activity diary data were collected at 15-min intervals, coding six different locations, and with space to record activities such as cooking and nearby smoking.

Sampling Methods

Two air sampling instruments were included in each participant's backpack. One 24-h filter sample of $PM_{2.5}$ was collected daily from the sampler in each backpack. A passive nephelometer (MIE DataRAM; Thermo-Electron) logging $PM_{2.5}$ at 15-min intervals was also attached to the backpack. Outdoor school-site concentrations of particles were also monitored at the ground level, outside each school during each field campaign at the NYU Particulate Matter Health Research Center's mobile air monitoring van. Personal $PM_{2.5}$ and EC, and school-site $PM_{2.5}$ and EC, were collected during each of the field campaigns. Details of the personal and school-site sampling methods, including instruments employed (Table S1) and EC determination, (Figure S1), can be found in Supplementary Material online (Chow et al., 1993; ISO, 1993; NIOSH: Manual of Analytical Methods (NMAM), 1998).

Continuous measurements of $PM_{2.5}$ (TEOM) from the New York Department of Environmental Conservation monitoring site on the rooftop of the PS154 school site were

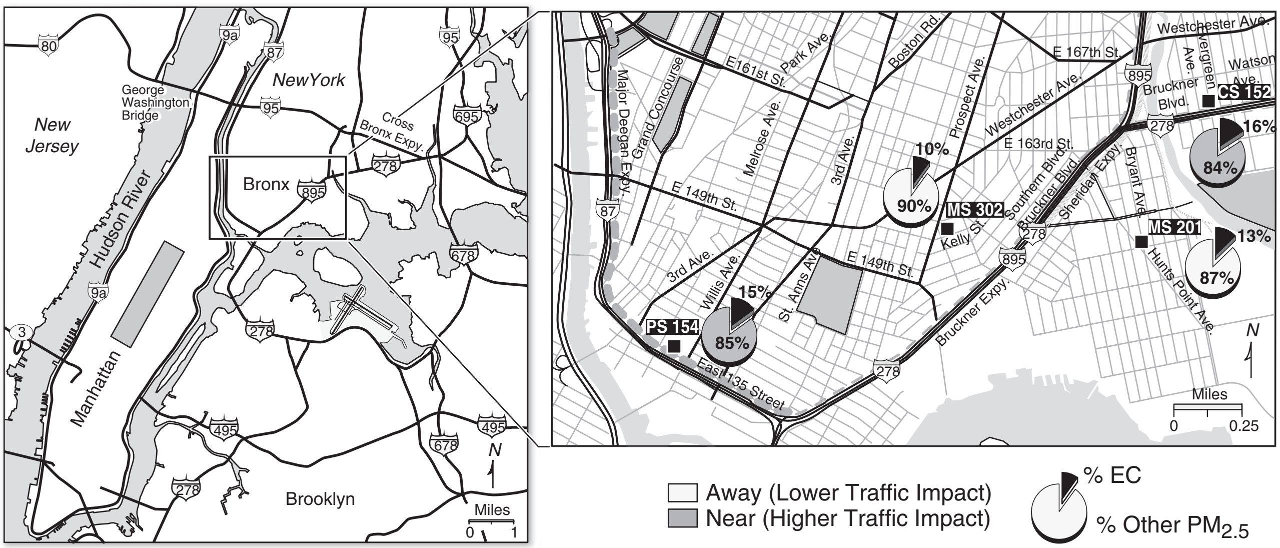

Figure 1. Traffic impact is significantly higher at schools beside the South Bronx's highways. The thickness of the dotted lines on highways is proportional to traffic flow.

also available for the duration of each sampling campaign. School-site sulfur concentrations were determined through X-Ray Fluorescence analysis at NYU's Sterling Forest laboratory, according to Maciejczyk et al. (2004).

Traffic Data

To allow comparisons between air quality and highway traffic levels, traffic counters (TRAX1; JAMAR Instruments, Horsham, PA, USA) were placed on the north and south sides of the Major Deegan Expressway and access roads during the last week of sampling at the adjacent school, PS154, from 11–17 May 2002. Traffic counters recorded vehicle numbers by vehicle class, which were then divided into car and truck categories, and tabulated by 15-min interval counts.

Quality Assurance

Out of a total of 990 subject-observation days, 270 occurred on weekend or school holidays, and personal filter samples were not collected on those days. School-site monitoring was carried out on both weekdays and weekends. Fifteen personal filter samples were removed from the analysis because of equipment malfunction, or if the backpack was not with the participant on that day. As a result, a total of 606 personal filter concentrations were available for the exposure analysis with corresponding outdoor school-site data.

Co-located school-site measurements were inter-compared. Twenty-four-hour averages were computed from the continuous measurements of BC measured at the four outdoor school sites and were regressed on the estimated EC concentrations (by the reflectance method) from the co-located filters. This relationship was used to adjust the 24-h averages of the school-site BC measurements to the EC concentrations estimated using the reflectance method. Similarly, 24-h average concentrations of the continuous TEOM measurements were also checked by regressing on the co-located gravimetrically determined $PM_{2.5}$ filter masses to insure a valid comparison with the personal filters. The personal nephelometer measurements were also regressed on the co-located measurements of personal filter $PM_{2.5}$ mass, and nephelometer measurements were adjusted accordingly.

EC as Diesel PM Marker

As an added test of the validity of our EC measurements as representative of a diesel emissions source in the South Bronx, we examined the organic profile of two of our daily samples. These samples were selectively chosen to be 1 day with high estimated EC concentrations and the other with low estimated EC concentrations in order to compare relative concentrations of the organic components for the extremes in EC exposure. Thermal desorption-gas chromatography/mass spectrometry analyses were carried out by the Wisconsin State Laboratory of Hygiene on two $PM_{2.5}$ outdoor school-site samples collected on the quartz filters at PS154. A chemical mass balance (CMB) receptor model was applied to these results according to Sheesley et al. (2009) (see also Lough et al. (2007)). The results from this analysis are limited due to the fact that financial constraints prevented us from analyzing the organic profile of more samples.

Data Analysis

Exposure relationships over time were characterized by evaluating the subject-specific correlations between personal and school-site $PM_{2.5}$ and EC. To predict ambient contributions to personal exposure measurements of EC and $PM_{2.5}$, linear mixed models were also applied. These models have been used to quantify the influence of outdoor pollution to both indoor and personal exposure (Wallace et al., 2003; Williams et al., 2003; Koutrakis et al., 2005; Sarnat et al., 2005; Jacquemin et al., 2007). Mixed effect models, which control for bias due to repeated observations on the same individual, were applied in this analysis using a subject-intercept random effects term. The parameters from these models include the model slope, which represents the fraction of the ambient concentration that contributes to personal exposure, and the model intercept, which represents the personal exposure from non-ambient sources. Models were run in Splus 6.1 v.3 (Insightful Corporation). The linear mixed model applied here is of the form

$$y_{ij} = \sum_m x_{ijm}\beta_m + b_i + e_{ij}$$

where, in this case, y_{ij} is the personal exposure concentration for the ith subject on the jth day for $i = 1,\ldots,40$, $j = 1,\ldots,n_{ij}$. Fixed effects variables, as x's, are the $PM_{2.5}$ mass or EC and any covariates. One random effects term is included, that is, b_i is the variation due to observations clustered by subject. e_{ij} represents the natural variation from noise. β_m is the parameter estimate for m number of fixed effects and any covariates.

Pooled models of exposure data across all four schools and interaction models of pollution with school (as a 4-level categorical variable) were evaluated. Slopes by school were computed from the models with an interaction term. Temperature was checked as a potential confounder. Pet ownership was also evaluated as a confounder in these models, as pet ownership can be a significant source of resuspended particles (Cortez-Lugo et al., 2008). The analysis was limited to weekday measurements, as personal exposure measurements did not include weekends. Two days were excluded from the regression analysis due to lack of data or suspect equipment functioning, and one outlying participant was excluded due to limited data and negative correlations with the school-site monitor. Total sample size was therefore reduced to 583 subject-observation days.

Traffic Exposure Impact and Home Distance Analysis

To assess the general impact of traffic-generated air pollution, we examined the relationship of exposure variables with traffic counts for the 5 days at PS154 using traffic count data. Variations in pollutants over time were also examined and evaluated in the context of general traffic patterns in the area.

The impact of distance from a highway on particle pollution exposure was assessed in a cross-sectional analysis of the relationship of personal exposure with home distance to the nearest highway. To determine the distance from each participant's home to the nearest highway, highways were mapped using longitude and latitude from US DOT files, and school and home addresses were geo-coded using GIS software (ArcGIS v. 9.1). The shortest distance (in feet) between the centers of both end points was determined using GIS. The distances were compared, using simple linear regression models, with the average particle pollution exposure for each participant over the study period. The analysis was limited to participants with available home addresses who lived within 1000 ft of a highway ($n = 23$). In addition, mean personal EC and $PM_{2.5}$ pollution, and the $EC/PM_{2.5}$ fraction were compared between participants living < 500 ft with those living > 500 ft from a highway.

Sensitivity Analyses

Although we targeted children from non-smoking households, some children had more reported minutes of environmental tobacco smoke (ETS) exposures than others. As a sensitivity analysis, we compared results including and excluding participants exposed to relatively higher levels of ETS. Participants with high ETS exposure were considered those with more than 30 min of exposure over the entire sampling period as recorded in the time–activity diaries. Nine participants were considered as those exposed to high ETS relative to the remaining 31 participants based on the criteria of 30 min of total ETS exposure. In another analysis, the sensitivity of our model to the influence of each school was also evaluated by excluding each school, and then re-evaluating the model coefficients for comparison with the full mixed model.

Results

Quality Assurance

The NYU van's aethelometer consistently indicated higher PM BC levels than the EC concentration estimated from the filter reflectance, but were highly correlated with the estimated EC at $r = 0.98$ (Pearson's r) over time. The BC measurements from the aethelometer were therefore adjusted to be consistent with the filter EC reflectance method by multiplying using the regression coefficient ($\beta = 0.60$). $PM_{2.5}$ mass measurements from the van TEOM showed a slope consistent with (not statistically different from) a one-to-one relationship with the filter-based $PM_{2.5}$, and did not require adjustment. The personal DataRAM nephelometers consistently read higher than the personal filter-based $PM_{2.5}$ samples, and were therefore also adjusted to the gravimetric measurements.

EC as Diesel PM Marker

In the organics analysis of two South Bronx filter samples, we were able to measure concentrations of several key organic compounds useful for separating spark ignition vehicle emissions from diesel emissions, including benzo[ghi]-perylene, indeno[1,2,3-c,d]pyrene and coronene (Lough et al., 2007). Application of source apportionment techniques using CMB modeling (according to Sheesley et al., 2009;

Lough et al., 2007) confirmed that the great majority of the EC in our samples (>90%) originated from diesel vehicles rather than from gasoline-powered vehicles or ''smoker'' cars (Table 1). Thus, we conclude that the difference in concentration between the low EC sample and the high EC sample analyzed is likely due primarily to an increase in diesel emissions. These results, although limited, are consistent with our assumption that EC is an indicator of diesel PM in this highly trafficked urban locale surrounded by major truck routes.

Descriptive Statistics

The overall mean personal EC concentration across all four schools was $1.9 \pm 1.4\,\mu g/m^3$, and the mean personal $PM_{2.5}$ concentration was $24.1 \pm 22.4\,\mu g/m^3$. The mean outdoor school-site EC concentration was $1.9 \pm 1.1\,\mu g/m^3$ and the mean outdoor school-site $PM_{2.5}$ concentration was $14.3 \pm 7.4\,\mu g/m^3$. The highest outdoor school-site concentrations of both $PM_{2.5}$ and EC were measured at MS302 (Table 2). In addition, excluding the two highest pollution days at MS302 (which coincided with stagnant meteorological conditions) significantly reduced the school-site concentrations of EC (see Table 2 footnote). Sulfur levels at this school were significantly higher than at the three other schools (Table 2), and school-site $PM_{2.5}$ was highly correlated with sulfur concentrations at this school. The lowest mean personal $PM_{2.5}$ concentrations were measured at CS152, the only school sampled in the fall (Table 2). No significant differences were found in mean $PM_{2.5}$ levels between the rooftop NY DEC monitor at PS154 and the ground-level monitors at any of the outdoor school sites. EC comprised ~7% of total personal $PM_{2.5}$ exposure on a daily basis, whereas the average daily EC/$PM_{2.5}$ fraction from the outdoor school-site data was ~13%.

Overall, the EC index derived using reflectance of the $PM_{2.5}$ filters from the personal backpack samplers was only moderately correlated with total $PM_{2.5}$ mass accumulated on the same filter ($r = 0.43$), indicating variable composition (and sources) of the personal $PM_{2.5}$ mass over time. Exposure to indoor sources of $PM_{2.5}$ mass was significant, as personal $PM_{2.5}$ measurements were significantly higher than outdoor school-site measurements ($P < 0.05$, by standard two-sample *t*-test). Personal EC levels, on the other hand, were generally equivalent or lower than outdoor school-site measurements.

Time–activity diary data showed that the participants spent, on average, more than 90% of their time indoors, 60–70% of their time at home, and 20–30% of their time indoors at another place. Only 7–10% of their time was spent outdoors or in transit. Most children lived within the near vicinity of the school and walked (or rode) to school between the hours of 0700–0800.

Traffic Exposure Impact and Home Distance Analysis

In agreement with recent traffic studies (Partnership for New York City, 2006), our traffic count data show a clear morning truck traffic peak, with a later and smaller afternoon peak, followed by relatively low traffic counts at night (Figure 2). The outdoor school-site EC concentrations collected simultaneously at PS154 showed the same pattern, with the most pronounced peak in the early morning. In addition, outdoor school site and rooftop PS154 $PM_{2.5}$ concentrations also showed a morning peak. When EC was subtracted from total $PM_{2.5}$, the peak flattened (Figure 3), indicating that the peak is related to localized traffic pollution. This morning pollution peak is also evident in an aggregate of the personal $PM_{2.5}$ measurements derived from the personal DataRAMs, also coinciding with the morning rush hour traffic peak, and showing a peak height relative to the status of home distance from a highway (Figure 4).

Outdoor school-site weekend data did not show this morning pollution spike; hence, weekday morning hours were found to be a time of especially high exposure to traffic-related PM pollution. During this time, children were most often on their way to school (0700–0800 hours weekdays), and the average outdoor school-site EC concentration was $3.0\,\mu g/m^3$. During the same time period on weekends, average school-site EC was only $1.4\,\mu g/m^3$. The time–activity

Table 1. CMB source apportionment of total organic carbon and elemental carbon concentrations determined using the non-polar thermal desorption-gas chromatography mass spectrometry method for one high and one low elemental carbon day in the South Bronx.

	Low EC day (22 October 2004) (EC = 2.1 $\mu g/m^3$) ($PM_{2.5}$ = 9.1 $\mu g/m^3$)		High EC day (29 October 2004) (EC = 6.1 $\mu g/m^3$) ($PM_{2.5}$ = 21.6 $\mu g/m^3$)	
	Percent OC contribution (uncertainty)	Percent EC contribution (uncertainty)	Percent OC contribution (uncertainty)	Percent EC contribution (uncertainty)
Biogenic burning	2.6 (0.4)	0.06 (0.01)	0.7 (0.1)	0.02 (0.004)
Diesel vehicles	53.9 (11.9)	92.6 (20.4)	30.9 (6.1)	93.5 (18.6)
Gasoline vehicles	38.2 (4.7)	7.36 (0.91)	15.3 (2.2)	5.2 (0.8)
''Smoker'' cars	5.2 (5.2)	0.07 (0.07)	53.0 (5.8)	1.2 (0.1)

Table 2. Personal and outdoor school-site pollutant levels[a].

Pollutant ($\mu g/m^3$)	Personal		School site[a]		PS154 rooftop (NY DEC)	
	24-h Mean ± SD	24-h Median	24-h Mean ± SD	24-h Median	24-h Mean ± SD	24-h Median
**PS154 (173 ft)*[b]						
29 April–19 May 2002	$N=135$		$N=15$		$N=15$	
$PM_{2.5}$	30.7 ± 6.8	30.6	14.1 ± 4.3	12.6	13.0 ± 5.0	11.5
EC	1.7 ± 0.6	1.5	2.1 ± 0.8	2.2		
$EC/PM_{2.5}$	0.07 ± 0.02	0.06	0.15 ± 0.03	0.15		
S			0.9 ± 0.4	0.9		
MS302 (1216 ft)[b]						
4–28 May 2004	$N=160$		$N=25$		$N=25$	
$PM_{2.5}$	32.7 ± 9.3	29.6	21.0 ± 10.8	17.3	22.6 ± 11.2	18.3
EC	2.4 ± 1.0	2.1	2.3 ± 1.6	1.6		
$EC/PM_{2.5}$	0.08 ± 0.02	0.08	0.10 ± 0.02	0.10		
S			1.9 ± 1.0	1.8		
**CS152 (128 ft)*[b]						
12 October–4 November 2004	$N=139$		$N=18$		$N=18$	
$PM_{2.5}$	25.8 ± 5.4	25.4	11.4 ± 3.2	11.0	10.2 ± 2.8	10.0
EC	1.7 ± 0.7	1.4	1.9 ± 1.0	1.3		
$EC/PM_{2.5}$	0.08 ± 0.04	0.07	0.16 ± 0.06	0.14		
			0.6 ± 0.2	0.6		
MS201 (2419 ft)[b]						
3–31 May 2005	$N=172$		$N=19$		$N=19$	
$PM_{2.5}$	32.2 ± 7.5	33.3	10.8 ± 2.9	10.7	10.9 ± 4.1	9.5
EC	1.5 ± 0.5	1.5	1.4 ± 0.5	1.3		
$EC/PM_{2.5}$	0.06 ± 0.02	0.06	0.13 ± 0.03	0.12		
S			0.7 ± 0.4	0.7		

School-site EC = BC measurements from aethelometer calibrated to estimated EC from co-located filters.
*Schools adjacent to highways.
Excluding the two highest pollution days at MS302, means decreased to: personal $PM_{2.5} = 29 \pm 8\,\mu g/m^3$; personal $EC = 2.0 \pm 0.4\,\mu g/m^3$; school-site $PM_{2.5} = 18 \pm 7\,\mu g/m^3$; school-site $EC = 1.7 \pm 0.6\,\mu g/m^3$; PS154 rooftop $PM_{2.5} = 20 \pm 8\,\mu g/m^3$.
[a]Limited to weekdays only 9am–9am average.
[b]Distance from nearest South Bronx highway.

diary data also indicated that at this time on weekends, most children were at home indoors.

School proximity to the highways showed a differential impact on the fraction of EC present in the $PM_{2.5}$ total mass at the outdoor school sites (Figure 1). The fraction of EC in $PM_{2.5}$ at the two schools that were located closest to major highways was significantly greater ($P<0.05$) than at the two schools located further away, despite the fact that absolute levels of pollution varied (largely because the schools were not sampled simultaneously).

Participants residing closer (<500 ft) to a highway had significantly higher mean personal EC exposure ($P<0.05$), mean personal $EC/PM_{2.5}$ fraction ($P<0.05$), and mean personal $PM_{2.5}$ mass ($P<0.05$) than those living further away (>500 ft) from a highway. In an aggregate of the personal dataRAM measurements, participants living within 500 ft of a highway also had significantly higher at-home $PM_{2.5}$ exposures ($P<0.01$), yet similar exposures while at school (Figure 4). After excluding high ETS-exposed participants in our sensitivity analysis, mean personal filter $PM_{2.5}$ became significantly higher for the group living closer to the highway ($P=0.05$). Increasing the threshold distance from 500 ft to the median home distance of 800 ft resulted in

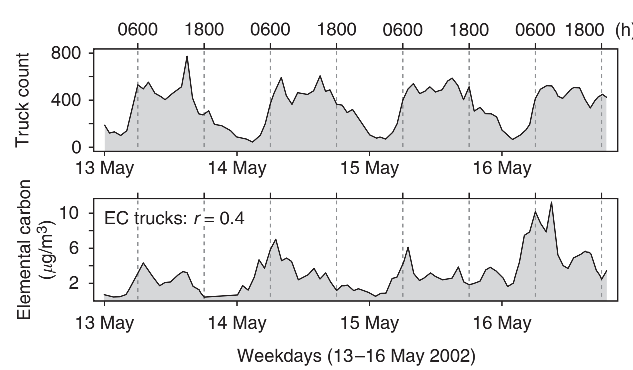

Figure 2. School-site EC pollution at PS154 was closely related to hourly variations in Major Deegan highway truck traffic. Elemental carbon = black carbon from continuous aethelometer.

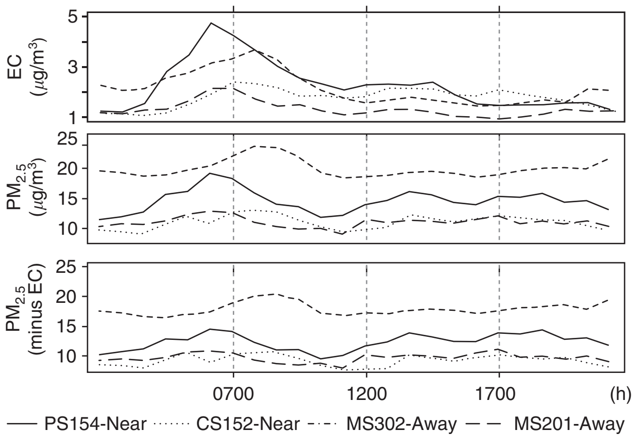

Figure 3. School-site $PM_{2.5}$ and EC hourly averages show a weekday rush hour peak at all four schools. Subtracting the EC concentrations from the PM reduces the peak.

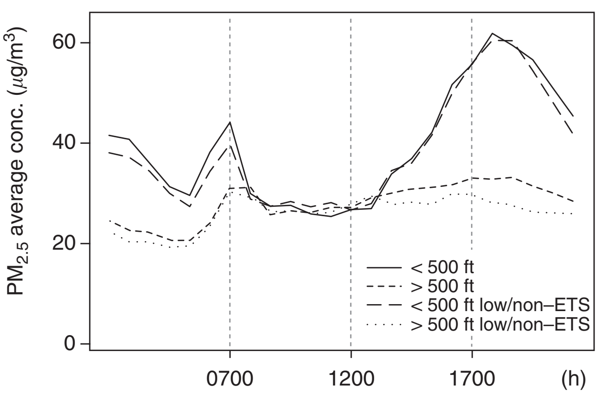

Figure 4. Personal $PM_{2.5}$ measurements averaged hourly across participants show a weekday morning $PM_{2.5}$ pollution peak. All participants with available data (total $n = 35$). Exclusion of participants exposed to >30 min of ETS during the study (total $n = 27$).

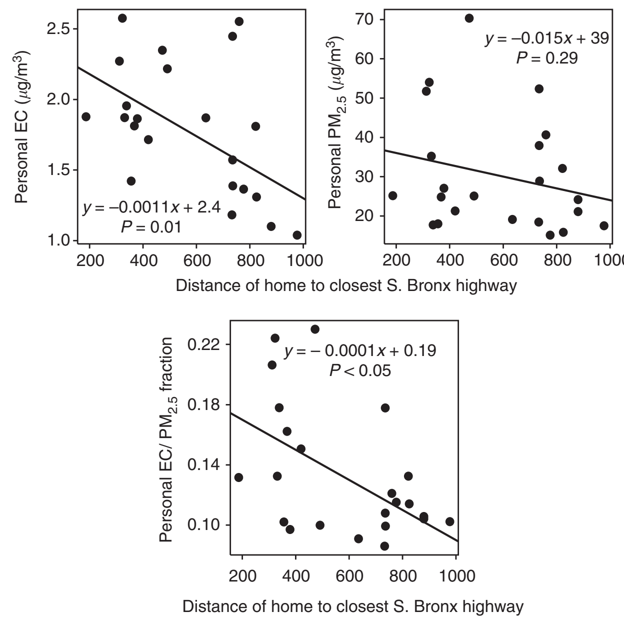

Figure 5. Home distance from a highway is significantly associated with mean personal EC concentration, mean personal $EC/PM_{2.5}$ fraction, but not mean total $PM_{2.5}$. Analysis limited to participants living within 1000 ft from a highway ($n = 23$).

significantly higher mean EC in the group living closer to the highway. This was not found with $PM_{2.5}$ or $EC/PM_{2.5}$. Of participants whose homes were located within 1000 ft of a highway, home distance from the nearest highway was found to be a significant predictor of mean personal EC pollution and mean personal $EC/PM_{2.5}$ fraction, but not of mean personal $PM_{2.5}$ pollution (Figure 5). "Normalizing" the personal $PM_{2.5}$ exposures across schools by subtracting the rooftop PS154 $PM_{2.5}$ from the personal concentrations did not significantly change the $PM_{2.5}$ results. This "normalization" was not feasible for the personal EC exposures because of the lack of rooftop (NY DEC) monitoring data for EC.

Personal School-Site Exposure Relationships

Longitudinal correlations by participant of the personal EC with outdoor school-site EC were, in general, much higher than those of personal $PM_{2.5}$ with central-site $PM_{2.5}$ over time (median $r = 0.64$ *vs* $r = 0.33$) (Figure 6). Of the 40 participants, 23 had personal EC concentrations that correlated by at least $r = 0.50$ with the outdoor school-site EC concentrations. At the school closest to the most heavily traveled highway, 8 out of 10 children had estimated personal EC measurements that were highly correlated ($r \geqslant 0.60$) with the daily outdoor school-site measurements. Longitudinal correlations by participant were higher for personal EC with both outdoor school-site $PM_{2.5}$ and rooftop PS154 $PM_{2.5}$ (from NY DEC) than for personal $PM_{2.5}$ with outdoor school-site $PM_{2.5}$ (median $r = 0.55$, $r = 0.46$ *vs* $r = 0.33$) (Figure 6).

The personal-school site model pooling data across all four schools indicated that almost half of the outdoor school-site EC concentrations was contributing to personal exposure ($\beta = 0.49$, 95% CI: 0.40, 0.57), whereas $\sim 0.89\,\mu g/m^3$ (model intercept) of EC on the personal filter could not be accounted for by ambient EC (Table 3). For $PM_{2.5}$, the slope for the contribution of school-site $PM_{2.5}$ to personal $PM_{2.5}$ was 0.67 (95% CI: 0.44, 0.89), with an intercept of $21.3\,\mu g/m^3$ $PM_{2.5}$ (95% CI: 15.3, 27.3) (Table 3).

Based on the above results, this model predicts that, for an average personal $PM_{2.5}$ exposure level of $31\,\mu g/m^3$, and a model intercept of $21.3\,\mu g/m^3$, indoor sources contribute heavily to personal $PM_{2.5}$. In contrast, with an average personal EC exposure of $1.9\,\mu g/m^3$, the model predicts that $0.89\,\mu g/m^3$ comes from indoor sources. Thus, outdoor EC sources have a much larger influence on average personal EC exposure levels than do outdoor $PM_{2.5}$ sources on personal $PM_{2.5}$ exposure levels.

In our sensitivity analysis of school sites, when excluding MS302, the school with the highest $PM_{2.5}$ pollution levels due to a regional pollution episode, the slope decreased to only 0.45 (95% CI, 0.03, 0.88). The slope for the pooled model of rooftop PS154 $PM_{2.5}$ was 0.59 (95% CI: 0.38, 0.80), but reduced to only 0.30 (95% CI, −0.07, 0.68) when MS302 was excluded, and the model lost statistical significance. Excluding other schools did not significantly change the results. Therefore, the model's sensitivity to the exclusion of MS302 indicates that the high regional PM episode during that sampling period was likely overly influencing the high slope and the statistical significance of the pooled model of personal-school site $PM_{2.5}$.

In our sensitivity analysis of ETS exposure, excluding high ETS-exposed participants affected the $PM_{2.5}$ model coefficients, but not the EC model coefficients. When these participants were excluded from the $PM_{2.5}$ model, the slope decreased to 0.56 (95% CI: 0.29, 0.83) (including MS302) (Table 3) and to only 0.38 (95% CI: −0.01, 0.86) (excluding MS302), and became nonsignificant (data not shown). When these participants were excluded from the model predicting personal $PM_{2.5}$ exposure from rooftop PS154 (NY DEC) monitoring data, the model slope was similarly reduced (Table 3). Thus, personal $PM_{2.5}$ exposures were greatly influenced by ETS when present, unlike EC.

Differences in slope by school were estimated separately using an interaction term. The interaction term was highly significant in the personal-school site EC model ($P<0.001$), but not in the $PM_{2.5}$ models (both personal-school site and personal-rooftop PS154). For EC, PS154, the school with the highest traffic exposure impact, had the highest slope, and CS152, although also closer to traffic, had the lowest slope and was the only school sampled during the fall season and had the highest wind speed. MS302 had the highest slope for $PM_{2.5}$, although it did not reach statistical significance (Table 4).

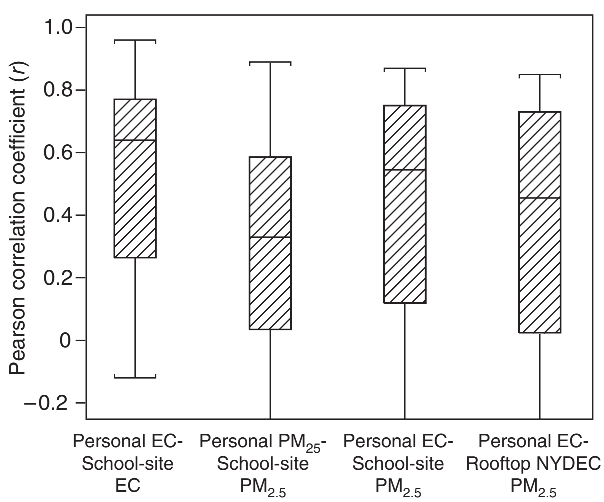

Figure 6. Longitudinal correlations of personal measurements with outdoor school-site monitors and with rooftop PS154 $PM_{2.5}$. Personal EC = estimated filter EC through reflectance. School-site EC = averaged continuous BC measurements to match filter sampling times.

Discussion

Evidence collected in our study collectively suggest a dominant role by diesel emissions in the EC soot exposures experienced by the participants in this study. The CMB analysis of the organic components on two South Bronx filters suggests that >90% of the EC on our filters was from diesel. However, the organics analysis was only based on two samples; hence, conclusions based on these results are limited. Additional indirect evidence indicating a diesel source for EC was from our traffic data, which showed that times of high school-site EC levels coincided with high numbers of trucks on the adjacent highway at PS154 (Figure 2). In addition, school proximity to the highways showed a differential impact on the school-site EC/$PM_{2.5}$ fraction (Table 2), with fractions of 15 and 16%, respectively, at the schools closest to highways. This EC/$PM_{2.5}$ fraction is much higher than that found in another study with little traffic pollution contributing to measured EC concentrations (Sarnat et al., 2006).

Early mornings were identified, in both personal and school-site data, as a time of day of particularly high $PM_{2.5}$ and EC exposure levels, which coincides with not only a rush

Table 3. Personal-school site mixed model intercepts and slopes and their 95% CI's.

	Personal EC–school-site EC		Personal $PM_{2.5}$–school-site $PM_{2.5}$		Personal $PM_{2.5}$–rooftop PS154 $PM_{2.5}$ (NY DEC)	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
All subjects ($N=583$)	**0.89 (0.63–1.14)**	**0.49 (0.40–0.57)**	**21.3 (15.3–27.3)**	**0.67 (0.44–0.89)**	**22.5 (16.7–28.4)**	**0.59 (0.38–0.80)**
Excluding MS302 subjects ($N=423$)	**0.72 (0.53–0.91)**	**0.43 (0.35–0.66)**	**24.0 (17.3–30.6)**	**0.45 (0.32–0.53)**	**26.9 (19.2–34.6)**	0.30 (−0.07–0.68)
Excluding ETS exposed subjects ($N=478$)	**0.84 (0.58–1.10)**	**0.49 (0.38–0.56)**	**22.0 (15.0–29.0)**	**0.56 (0.29–0.83)**	**23.1 (16.3–30.0)**	**0.49 (0.24–0.74)**

The bold values signify $P<0.05$ for $\beta\neq0$.
Coefficients of determination (r^2) for predicted *vs* actual = 0.35–0.41 for EC models, and 0.52–0.56 for PM models.

hour traffic peak but also a generally lower mixing height that inhibits pollution dispersion in the morning hours. Thus, some of the children's highest exposures to traffic-related air pollution during the day were indicated by this study to be during their morning walk/ride to school. In fact, we found that EC concentrations were twice as high during weekday mornings than on weekends during the morning hour (0700–0800 hours), which children were on their way to school.

In a previous analysis using GIS-based methods, we estimated that $\sim$44% of the children's school-time personal $PM_{2.5}$ exposure at PS154 was from traffic on the Major Deegan Expressway and on ramps in front of the school (Spira-Cohen et al., 2004), suggesting the dominance of this source of pollution for children attending PS154. The strong longitudinal correlations between school site and personal exposures combined with the large mixed model slope at PS154 serve to confirm the high traffic impact on personal exposure levels at PS154.

Our findings of higher subject-specific longitudinal personal school-site correlations for EC (median: $r = 0.64$) than for total $PM_{2.5}$ mass (median: $r = 0.33$) are consistent with the results of prior studies showing median correlations of total $PM_{2.5}$ to be lower than those of PM components of predominantly outdoor origin (Sarnat et al., 2005; Noullet et al., 2006). As infiltration tends to be lower in winter (Koutrakis et al., 2005; Sarnat et al., 2005; Brown et al., 2008) from closed windows and other modifying behaviors, this could explain the comparatively lower mixed model slope at CS152, which was sampled during October when the temperature was, on average, 3°C lower than experienced at the other three schools. In addition, average wind speeds at this school were also higher than at other schools. We were not able to evaluate the influence of seasonal and ventilation conditions in this study.

A potential limitation to personal exposure studies, including this one, is the possibility of modified behavior from carrying a personal monitor. However, in this case, we instructed the children to continue their routine activities as much as possible while placing the backpack nearby, and there was no direct evidence of any modified behavior in our panel of participants. If activities were indeed restricted, the error in estimating actual exposure would be greater in children because of their generally higher activity levels.

Although we monitored participants from predominantly non-smoking households we found in our sensitivity analysis of ETS that home distance analyses of PM exposure were influenced by ETS, whereas EC analyses were not (Table 3). This is consistent with the fact that carbon from cigarettes is largely considered organic carbon, not EC (Hildemann et al., 1991). When ETS-exposed participants were excluded from the distance analyses, we found significantly higher $PM_{2.5}$ concentrations for participants living closer (<500 ft) to a major highway, a higher peak in the early morning, and higher at home exposures for the participants living closer to a highway. EC mixed model slopes were also significant and robust to the influence of ETS and regional PM episodes. Thus, central-site EC is seen to be a useful index of PM pollution from localized traffic, and it is also highly correlated with personal EC exposure over time.

Our results linking home distance from a highway with elevated personal exposures of both EC and $PM_{2.5}$ support the validity of Van Roosebroeck et al.'s (2006) findings of a relationship of home (Van Roosebroeck et al., 2006) and school (Van Roosebroeck et al., 2007) distance from a highway to children's personal exposure in the Netherlands. This finding also gives credence to the use of distance exposure metrics in community-based epidemiological studies of children's health. Indeed, a significant statistical relationship was still able to be determined with distance from a highway even in such a high-density urban area. Although personal exposure to the traffic-related component is preferable for studies collecting individual-level health data, for the purposes of health effects assessments, our data indicate that distance from a highway is a useful surrogate for diesel PM impacts in larger scale studies where personal sampling is not feasible.

Our results also suggest that the use of central monitoring $PM_{2.5}$ data in high-traffic areas may be appropriate, as we found high correlations between personal EC and both outdoor school-site EC and $PM_{2.5}$. In fact, we found higher correlations of rooftop PS154 $PM_{2.5}$ (from the NY DEC

Table 4. Personal-school site mixed model intercepts and slopes and their 95% CI's by school from interaction model.

	Personal EC–school-site EC[a] ($N = 583$)		Personal $PM_{2.5}$–school-site $PM_{2.5}$ ($N = 583$)		Personal $PM_{2.5}$–rooftop PS154 $PM_{2.5}$ (NY DEC) ($N = 583$)	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
PS154	0.10 (−0.69–0.90)	**0.78 (0.49–1.06)**	**22.4 (3.2–41.6)**	0.60 (−0.40–1.60)	**24.5 (5.3–43.8)**	0.48 (−0.58–1.55)
MS302	**1.21 (0.53–1.89)**	**0.51 (0.31–0.71)**	16.1 (−2.0–34.2)	0.78 (−0.05–1.62)	15.4 (−3.4–34.1)	0.76 (−0.20–1.71)
CS152	**1.11 (0.60–1.52)**	**0.26 (0.09–0.43)**	**24.7 (10.8–38.7)**	0.22 (−0.58–1.01)	**26.4 (11.9–40.9)**	0.09 (−0.83–1.01)
MS201	**0.91 (0.09–1.72)**	**0.48 (0.07–0.89)**	**30.1 (10.1–50.1)**	0.31 (−0.90–1.53)	**32.6 (13.2–52.0)**	0.07 (−1.04–1.19)

[a]Interaction term significant at $P < 0.05$ for EC model only.
The bold values signify $P < 0.05$ for $\beta \neq 0$.
Coefficients of determination (r^2) for predicted *vs* actual = 0.35 for EC models, and 0.53 for PM models.

monitor) with personal EC than with personal $PM_{2.5}$, indicating that outdoor $PM_{2.5}$ mass measurements can be better surrogates for personal exposure to outdoor air pollution than personal $PM_{2.5}$ measurements (which can be overly affected by indoor sources, such as ETS, when present).

Rather than relying on indicators of exposure to traffic-generated particles, this study had the advantage of having personal exposure indices of EC, whose diesel origin in the study area was verified by correlations with traffic counts and through source apportionment of molecular markers. Participants living closer to a highway were found to have higher personal exposures to traffic-generated particles. This analysis also confirms that smoke emitted from diesel trucks is a significant contributor to personal $PM_{2.5}$ exposure levels in children in the South Bronx, NY, many of whom suffer from asthma, and may be particularly susceptible to health effects from these exposures.

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Conflict of interest

The authors declare no conflict of interest.

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