



Published in final edited form as:

J Expo Sci Environ Epidemiol. 2010 July ; 20(5): 446–456. doi:10.1038/jes.2009.34.

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

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Abstract

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 forty fifth-grade children. These students, from four South Bronx, NY schools, each carried air pollution monitoring equipment with them 24 hours per day for approximately one month. Daily EC concentrations were estimated using locally calibrated reflectance of the PM_{2.5} samples. Personal EC was more closely related to outdoor school-site EC (median subject-specific $r = 0.64$) than was personal PM with school-site PM_{2.5} (median subject specific $r = 0.33$). Regression models also showed a stronger, more robust association of school-site with personal measurements for EC than for PM_{2.5}. High traffic pollution exposure was found to coincide with the weekday early morning rush hour, with higher personal exposures for subjects 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 diesel vehicles, are a significant contributor to personal PM exposure levels of children living in urban areas such as the South Bronx, NY.

Introduction

Assessing the personal exposure impact of localized traffic pollution is critical in light of the variety of health effects that have been found to be associated with proximity to highways^{1,2,3,4,5,6}. Several proximity studies have particularly linked traffic exposure with adverse respiratory health effects^{7,1,8,9}. Traffic-related air pollution studies showing health effect associations have mainly relied on modeled exposure variables using traffic-density

metrics or GIS-based methods^{7,10,6,11}. Other studies have employed central-site measurements, or emissions inventories in combination with modeled or empiric traffic exposure indicators^{12,13,14,15,16}, including land use regression models¹⁷. Few health studies have measured personal exposure to traffic particles directly^{18,19,20}.

Previous studies have indicated that traffic-generated PM 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 Finland²¹. Traffic was also an important determinant of personal absorbance in Amsterdam and Helsinki²², and in Barcelona²³. In the U.S., where diesel vehicles are more limited to truck traffic, in Boston, MA, indoor EC levels were associated with distance from a truck route²⁴, and in Detroit, MI, diesel traffic on the Ambassador Bridge was found to contribute significantly to indoor EC levels of homes in the area²⁵. These findings suggest that localized diesel pollution could be a major contributor to personal exposure in populations living adjacent to highways and 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 not²⁴. Levels of both PM_{2.5} and reflectance “black soot” were correlated with increasing truck traffic density and proximity to a roadway^{26,27}. Although site-to-site variation in PM_{2.5} concentrations were modest in Harlem (a NYC community with high rates of asthma and traffic volumes), EC concentrations varied 4-fold across sites and were associated with bus and truck counts on adjacent streets²⁸.

Previous work by NYU in the S. Bronx area, including ground-level air quality monitoring at various South Bronx sites (2001–2003), also suggest EC to be traffic related in this particular locale²⁹. Maciejczyk et al. (29) compared S. Bronx ground-level concentrations and rooftop monitors at PS154 to concentrations measured at Hunter College on E. 25th street in Manhattan, and found significantly higher concentrations for black carbon (BC) at the S. 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 Point²⁷, 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 about 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 comprised of 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 employing reflectance techniques to

estimate concentrations of EC, an important component of Diesel Exhaust Particles (DEP), 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 utilize 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 elsewhere³⁰.

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 subjects were followed for approximately one 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 variety of traffic pollution exposures.

On every weekday of the study, subjects visited on-site NYU researchers twice daily to change air sampling filters and download motion sensor (HOBO) data. In the case of absences, the students were contacted by the study coordinator to collect the information. Subjects were instructed to keep the backpack near them at all times. If the motion sensor data indicated that the bag had not been with the child, then this was recorded in the sampling log and the exposure data excluded from the analyses. Time-activity diary data was collected at 15-minute intervals, coding 6 different locations, and with space to record activities such as cooking and nearby smoker.

Sampling Methods

Two air sampling instruments were included in each subject's backpack. One 24-hr filter sample of PM_{2.5} was collected daily from the sampler in each backpack. A passive nephelometer (MIE DataRam; Thermo-Electron Inc.) logging PM_{2.5} at 15-minute 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 online as supplemental material.

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 also available for the months of the sampling campaigns. School-site sulfur concentrations were determined via X-Ray Fluorescence analysis at NYU's Sterling Forest laboratory, as per Maciejczyk et al. (29).

Traffic Data

To allow comparisons between air quality and highway traffic levels, traffic counters (TRAX1; JAMAR Instruments, PA) 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 May 11th–17th, 2002. Traffic counters recorded vehicle numbers by vehicle class, which were mathematically collapsed into car and truck categories, and tabulated by 15 minute 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 subject 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 intercompared. Twenty-four hour averages were computed from the continuous measurements of black carbon 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 twenty-four hour averages of the school site black carbon measurements to the EC concentrations estimated via the reflectance method. Similarly, twenty-four hour 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 as one 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 (TD-GCMS) analyses were performed 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 as per Sheesley et al. (31) (see also Lough et al. (32)). 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 employed to quantify the influence of outdoor pollution to both indoor and personal exposure^{33,34,35,36,23}. 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 i^{th} subject on the j^{th} day for $i = 1, \dots, 40$, $j = 1, \dots, n_{ij}$. Fixed effects variables, as x 's, are the $\text{PM}_{2.5}$ mass or EC and any covariates. One random effects term is included: 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, since pet ownership can be a significant source of resuspended particles³⁷. The analysis was limited to weekday measurements, since 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 subject 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 five days at PS154 with 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 subject'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 endpoints was determined using GIS. The distances were compared, using simple linear regression models, with the average particle pollution exposure for each subject over the study period. The analysis was limited to subjects with available home addresses who lived within 1000 ft of a highway ($n=23$). Additionally, mean personal EC and $\text{PM}_{2.5}$ pollution, and the EC/ $\text{PM}_{2.5}$ fraction were

compared between subjects living within 500 ft vs. those living greater than 500 ft from a highway.

Sensitivity Analyses

Although we targeted children from non-smoking households, some children had more reported minutes of ETS exposures than others. As a sensitivity analysis, we compared results including and excluding subjects exposed to relatively higher levels of ETS. Subjects with high ETS exposure were considered those with more than 30 minutes of exposure over the entire sampling period as recorded in the time-activity diaries. Nine subjects were considered high ETS exposed relative to the remaining 31 subjects based on the criteria of 30 minutes 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 by 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 coronene³². Application of source apportionment techniques using CMB modeling (as per Sheesley et al. (31) and Lough et al. (32)) confirmed that the great majority of the EC in our samples (> 90%) originated from diesel vehicles, rather than 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, though 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 $1.9 \pm 1.4 \mu\text{g}/\text{m}^3$, and the mean personal PM_{2.5} concentration was $24.1 \pm 22.4 \mu\text{g}/\text{m}^3$. The mean outdoor school-site EC concentration was $1.9 \pm 1.1 \mu\text{g}/\text{m}^3$ and the mean outdoor school-site PM_{2.5} concentration was $14.3 \pm 7.4 \mu\text{g}/\text{m}^3$. 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 NYDEC monitor at PS154 and the ground-level monitors at any of the outdoor school-sites. EC comprised approximately 7% of total personal PM_{2.5} exposure on a daily basis, while the average daily EC/PM_{2.5} fraction from the outdoor school-site data was approximately 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, since 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 subjects 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 7–8am.

Traffic Exposure Impact and Home Distance Analysis

In agreement with recent traffic studies³⁸, 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. Additionally, outdoor school-site and rooftop PS154 PM_{2.5} concentrations also exhibited 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, so weekday morning hours were found to be a time of especially high exposure to traffic-related PM pollution. During the time children were most often on their way to school (7am–8am weekdays), the average outdoor school-site EC concentration was 3.0 µg/m³. During the same time period on weekends, average school-site EC was only 1.4 µg/m³. Time-activity 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).

Subjects 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 subjects living further away (> 500 ft) from a highway. In an aggregate of the personal dataRAM measurements, subjects 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 subjects 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 feet to the median home distance of 800 ft resulted in 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 subjects 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 lack of rooftop (NY DEC) monitoring data for EC.

Personal- School Site Exposure Relationships

Longitudinal correlations by subject of the personal EC with outdoor school-site EC were, in general, much higher than correlations of personal PM_{2.5} with central-site PM_{2.5} over time (median $r = 0.64$ vs. $r = 0.33$) (Figure 6). Twenty-three (23) of the 40 subjects 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, eight out of ten children had estimated personal EC measurements that were highly correlated ($r = 0.60$) with the daily outdoor school-site measurements. Longitudinal correlations by subject 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 just under half of the outdoor school-site EC concentrations was contributing to personal exposure ($\beta = 0.49$, 95% CI, 0.40 to 0.57), while approximately $0.89 \mu\text{g}/\text{m}^3$ (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 $21.3 \mu\text{g}/\text{m}^3$ PM_{2.5} (95% CI, 15.3, $27.3 \mu\text{g}/\text{m}^3$) (Table 3).

Based on the above results, this model predicts that, for an average PM_{2.5} personal exposure level of $31 \mu\text{g}/\text{m}^3$, and a model intercept of $21.3 \mu\text{g}/\text{m}^3$, indoor sources contribute heavily to personal PM_{2.5}. In contrast, with an average personal EC exposure of $1.9 \mu\text{g}/\text{m}^3$, the model predicts that $0.89 \mu\text{g}/\text{m}^3$ 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 dropped 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 subjects affected the PM_{2.5} model coefficients, but not the EC model coefficients. When these subjects were excluded from the PM_{2.5} model, the slope dropped 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 non-significant (not shown). When these subjects 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 windspeed. MS302 had the highest slope for PM_{2.5} although it did not reach statistical significance (Table 4).

Discussion

Evidence collected in our study collectively suggest a dominant role by diesel emissions in the elemental carbon soot exposures experienced by the subjects 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, and therefore 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% at the schools closest to highways. This EC/PM_{2.5} fraction is much higher than found in another study with little traffic pollution contributing to measured EC concentrations³⁹.

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 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 (7–8am) that children were on their way to school.

In a previous analysis using GIS-based methods, we estimated that roughly 44% of the children's school-time personal PM_{2.5} exposure at PS154 was coming from traffic on the Major Deegan Expressway and on-ramps in front of the school⁴⁰, 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 correlations of PM components of predominantly outdoor origin^{41,36}. Since infiltration tends to be lower in winter^{36,35,42} 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 degrees lower than experienced at the other three schools. In addition, average wind speeds at this school were also higher than at the other schools. We were not able to evaluate the influence of seasonal and ventilation conditions in the current 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 subjects. 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 subjects 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 as organic carbon, not elemental carbon⁴³. When ETS exposed subjects were excluded from the distance analyses, we found significantly higher PM concentrations for subjects living closer (< 500 ft) to a major highway, a higher peak in the early morning, and higher at home exposures for the subjects 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 support the validity of Van Roosbroeck et al's findings of a relationship of home⁴⁴ and school⁴⁵ 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 the 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, since 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 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 rely on indicators of exposure to traffic-generated particles, this study had the advantage of having personal exposure indices of elemental carbon, whose diesel origin in the study area was verified by correlations with traffic counts and via source apportionment of molecular markers. Subjects living closer to a highway were found to have higher personal exposures to traffic-generated particles. This analysis also confirms that diesel trucks are a significant contributor to personal PM_{2.5} exposure levels of children in the South Bronx, NY, many of whom suffer from asthma, and may be particularly susceptible to health effects from these exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work is supported by the Health Effects Institute (HEI), and the NYU-NIEHS Center of Excellence Grant ES00260, and by the EPA under grant no. R827351 (Agreement No. X-982152) and under the Science to Achieve Results (STAR) Graduate Fellowship Program. The views expressed herein may not reflect the views of the EPA. The collaboration of the New York City School System and South Bronx community group partners (Youth Ministries for Peace and Justice, The Sports Foundation, Nos Quedamos, The Point CDC) were essential to the completion of this research. Special acknowledgement to Dritan Xillari, Jessica Clemente, Martin Blaustein, John Gorczynski, Ramona Lall, Sarah Langan, Jeff DeMinter and Dr. James Schauer, who made significant contributions to this research.

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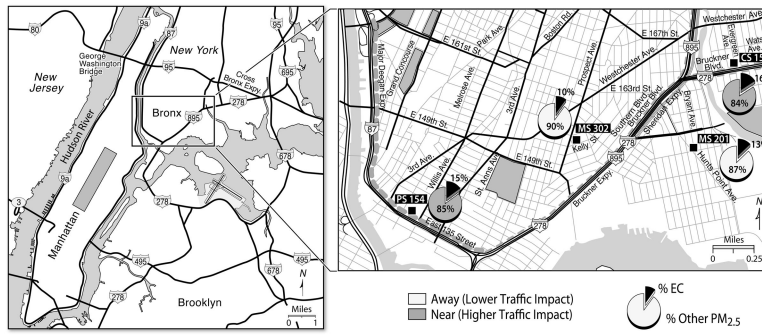


Figure 1.
 Traffic impact is significantly higher at schools beside the Bronx’s highways.
 The thickness of the dotted lines on highways is proportional to traffic flow.

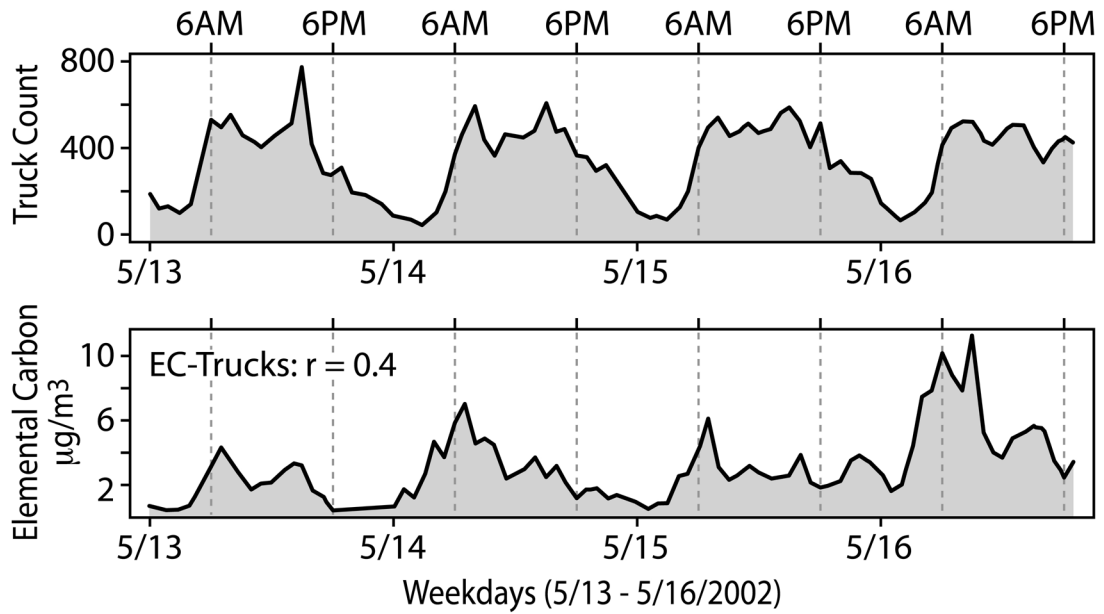


Figure 2. School-site EC pollution at PS154 was closely related to hourly variations in Major Deegan highway truck traffic.
Elemental Carbon = Black Carbon from continuous aethelometer

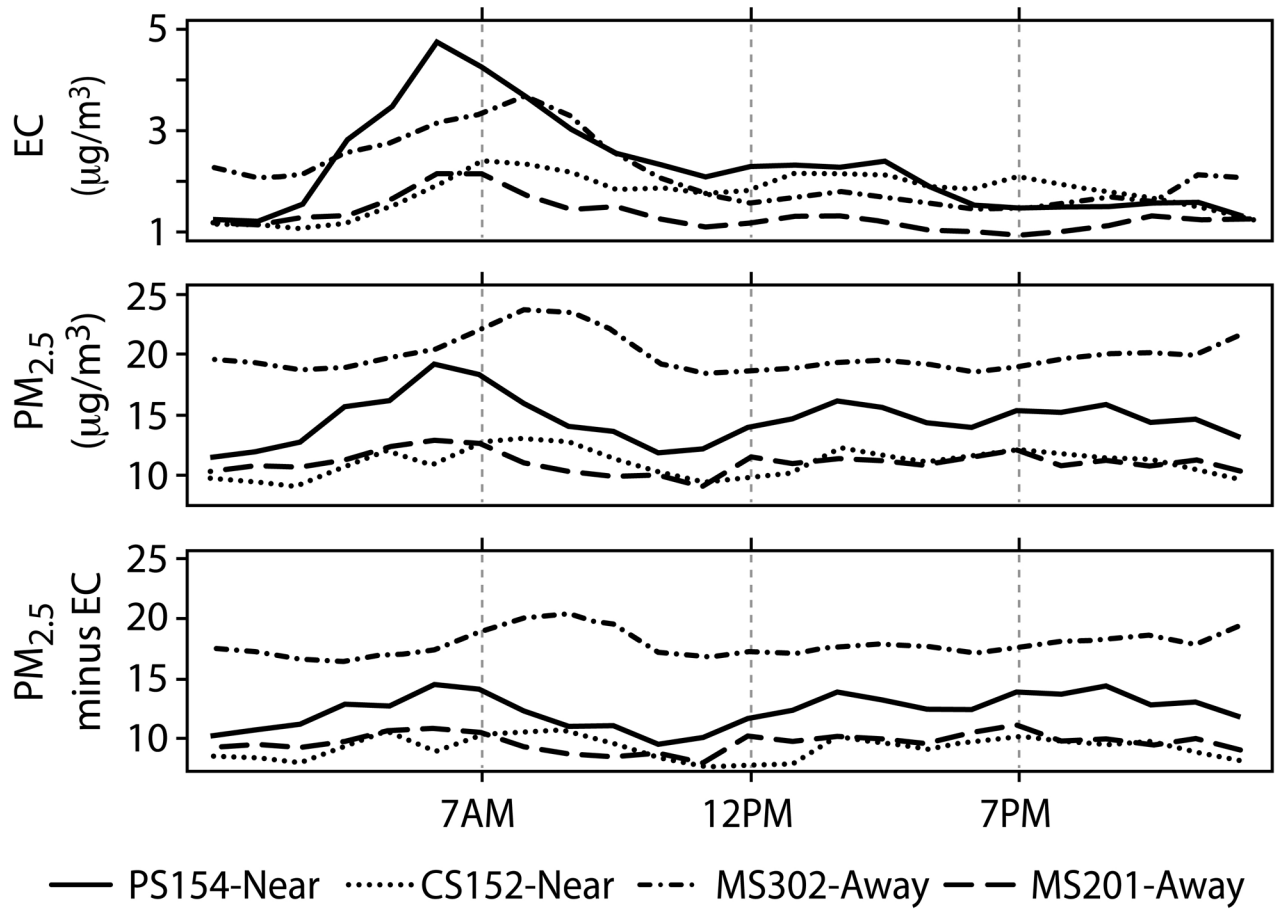


Figure 3. School-site PM_{2.5} and EC hourly averages show a weekday rush-hour peak at all four schools. Subtracting the EC concentrations from the PM reduces the peak.

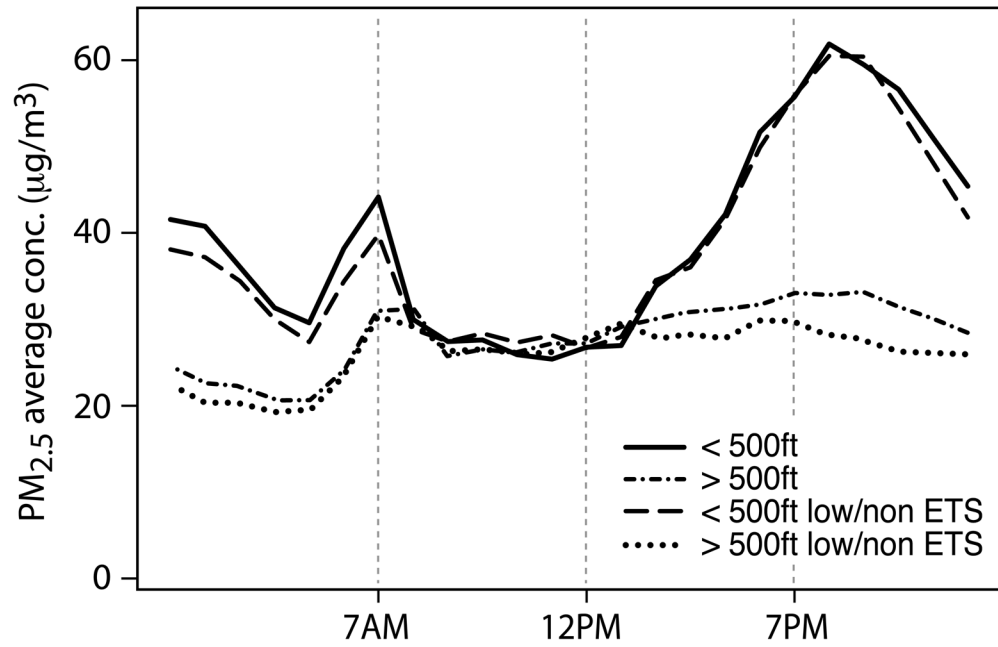


Figure 4.

Personal PM_{2.5} measurements averaged hourly across subjects exhibit a weekday morning PM_{2.5} pollution peak.

All subjects with available data (total n= 35). Exclusion of subjects exposed to >30 minutes of ETS during the study (total n=27).

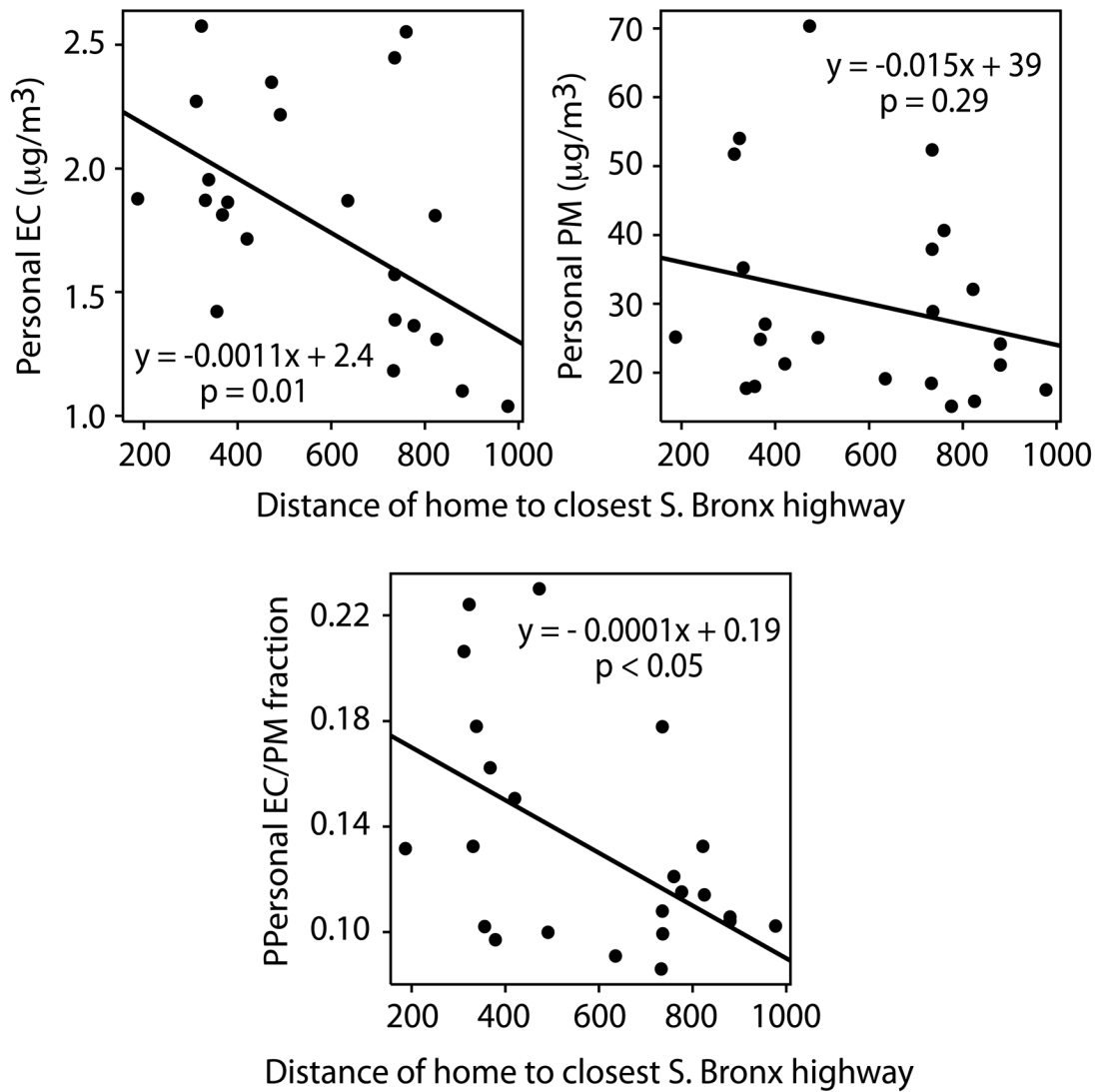


Figure 5. Home distance from a highway is significantly associated with mean personal EC concentration, mean personal EC/PM_{2.5} fraction, but not mean total PM_{2.5}. Analysis limited to subjects living within 1000ft of a highway (n=23)

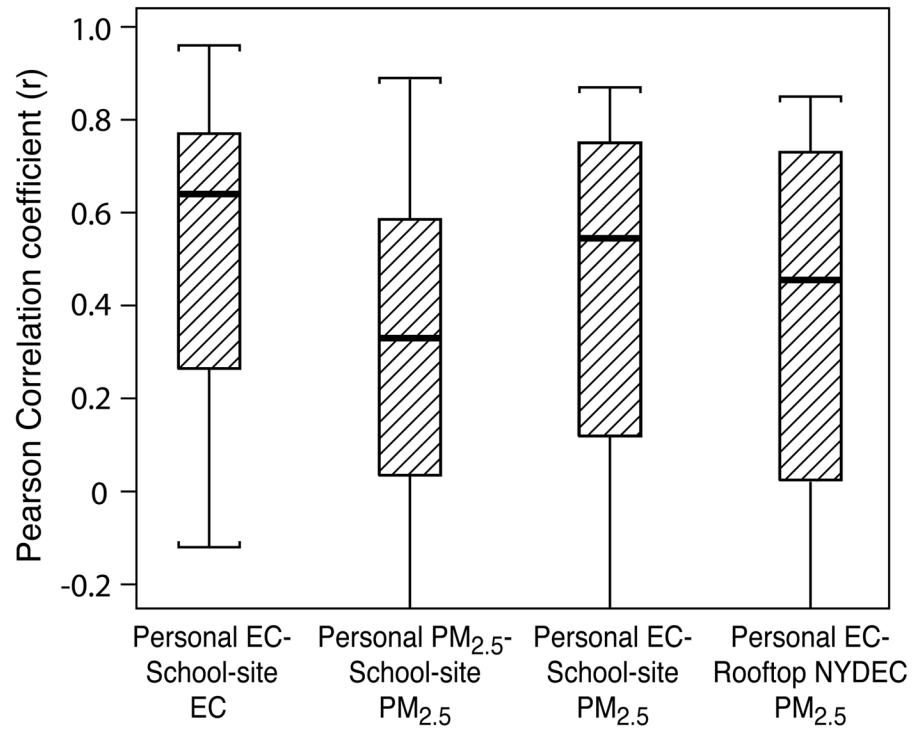


Figure 6.

Longitudinal correlations of personal measurements with outdoor school-site monitors and with rooftop PS154 PM_{2.5}.

Personal EC = estimated filter EC via reflectance

School-site EC = averaged continuous BC measurements to match filter sampling times

Table 1

CMB source apportionment of total organic carbon and elemental carbon concentrations determined via the non-polar TD-GCMS method for one high and one low elemental carbon day in the South Bronx

	<u>Low EC Day</u> (10/22/04) (EC = 2.1 $\mu\text{g}/\text{m}^3$) (PM _{2.5} = 9.1 $\mu\text{g}/\text{m}^3$)		<u>High EC Day</u> (10/29/04) (EC = 6.1 $\mu\text{g}/\text{m}^3$) (PM _{2.5} = 21.6 $\mu\text{g}/\text{m}^3$)	
	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[†]

Pollutant (ug/m ³)	Personal		School-site [†]		PS154 Rooftop (NY DEC)	
	24-hr Mean ± SD	24-hr Median	24-hr Mean ± SD	24-hr Median	24-hr Mean ± SD	24-hr Median
PS154 (173 ft.)^{††}						
April 29 th – May 19 th , 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 ± .6	1.5	2.1 ± .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.)^{††}						
May 4 th – May 28 th , 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.)^{††}						
Oct 12 th – Nov 4 th , 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 ± .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		
S			0.6 ± 0.2	0.6		
MS201 (2419 ft.)^{††}						
May 3 rd – May 31 st , 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 ± .5	1.5	1.4 ± 0.5	1.3		

Pollutant (µg/m ³)	Personal		School-site [†]		PS154 Rooftop (NY DEC)	
	24-hr Mean ± SD	24-hr Median	24-hr Mean ± SD	24-hr Median	24-hr Mean ± SD	24-hr Median
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 dropped to: Personal PM_{2.5} = 29±8; Personal EC = 2.0±4; School-site PM_{2.5} = 18±7; School-site EC = 1.7±6; PS154 Rooftop PM_{2.5} = 20±8

[†] Limited to weekdays only 9am-9am average

^{††} Distance from nearest S. Bronx highway

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 PSI54 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)

p < 0.05 for beta = 0

coefficients of determination (R^2) for predicted vs. actual = 0.35–0.41 for EC models, and 0.52–0.56 for PM models

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.* (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
PS154			
	0.10 (-0.69 – 0.90)	0.78 (0.49 – 1.06)	22.4 (3.2 – 41.6)
MS302			
	1.21 (0.53 – 1.89)	0.51 (.31 – 0.71)	24.5 (5.3 – 43.8)
CS152			
	1.11 (0.60–1.52)	0.26 (0.09 – 0.43)	15.4 (-3.4 – 34.1)
MS201			
	0.91 (0.09–1.72)	0.48 (0.07 – 0.89)	26.4 (11.9 – 40.9)
			32.6 (13.2 – 52.0)

* interaction term significant at p < 0.05 for EC model only

p < 0.05 for beta 0

coefficients of determination (R²) for predicted vs. actual = 0.35 for EC models, and 0.53 for PM models