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Spatial and Temporal Variations in Traffic-related Particulate Matter at New York City High Schools

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Abstract

Relatively little is known about exposures to traffic-related particulate matter at schools located in dense urban areas. The purpose of this study was to examine the influences of diesel traffic proximity and intensity on ambient concentrations of fine particulate matter (PM_{2.5}) and black carbon (BC), an indicator of diesel exhaust particles, at New York City (NYC) high schools. Outdoor PM_{2.5} and BC were monitored continuously for 4–6 weeks at each of 3 NYC schools and 1 suburban school located 20 kilometers upwind of the city. Traffic count data were obtained using an automated traffic counter or video camera. BC concentrations were 2–3 fold higher at urban schools compared with the suburban school, and among the 3 urban schools, BC concentrations were higher at schools located adjacent to highways. PM_{2.5} concentrations were significantly higher at urban schools than at the suburban school, but concentrations did not vary significantly among urban schools. Both hourly average counts of trucks and buses and meteorological factors such as wind direction, wind speed, and humidity were significantly associated with hourly average ambient BC and PM_{2.5} concentrations in multivariate regression models. An increase of 443 trucks/buses per hour was associated with a 0.62 µg/m³ increase in hourly average BC at a NYC school located adjacent to a major interstate highway. Car traffic counts were not associated with BC. The results suggest that

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local diesel vehicle traffic may be important sources of airborne fine particles in dense urban areas and consequently may contribute to local variations in $PM_{2.5}$ concentrations. In urban areas with higher levels of diesel traffic, local, neighborhood-scale monitoring of pollutants such as BC, which compared to $PM_{2.5}$, is a more specific indicator of diesel exhaust particles, may more accurately represent population exposures.

Keywords

Diesel Traffic; Particulate Matter; Black Carbon; Urban Air Pollution

1. Introduction

Elevated exposures to a complex mix of airborne pollutants and disproportionately high asthma prevalence and morbidity are among the environmental health challenges faced by New York City (NYC) residents (Kinney et al., 2000; Lena et al., 2002). In the year 2000, NYC asthma hospitalization rates averaged 33.6 per 10,000 residents, more than twice the national average of 16.7 per 10,000 residents (Garg et al., 2003). Additionally, the South Bronx and Northern Manhattan neighborhoods are consistently found to have the highest rates of pediatric asthma hospitalization, mortality, and school-based prevalence among NYC neighborhoods (SPARCS 2007). These neighborhoods house relatively high concentrations of highways, parking lots, bus and truck depots and other facilities and infrastructure that give rise to high volumes of vehicular traffic. These are significant contributors to air pollution exposures of New York City residents.

The NYC metropolitan statistical area (MSA) has been repeatedly cited as being out of attainment for fine particulate matter ($PM_{2.5}$) (EPA 2005). Whereas ten year trends for the NYC MSA have shown improvements in ambient air levels of carbon monoxide, sulfur dioxide, nitrogen oxides, and coarse particulate matter, little improvement has been observed in trends for $PM_{2.5}$ (EPA 2004). NYC's air quality problems are relevant given the consistent evidence linking ambient $PM_{2.5}$ concentrations to respiratory morbidity, particularly among children living in urban areas (Norris et al., 1999; Koenig et al., 2003; Gauderman et al., 2004; O'Connor et al., 2008).

Diesel exhaust particles (DEP) are significant local sources of $PM_{2.5}$ in urban areas (Laden et al., 2000; Fraser et al., 2003). Furthermore, in urban areas, emissions from heavy-duty diesel trucks and buses contribute significantly to ambient $PM_{2.5}$ concentrations that exceed National Ambient Air Quality Standards (NRC 2002). DEP concentrations display high spatial heterogeneity and are strongly influenced by local truck traffic density (Kinney et al., 2000; Lena et al., 2002) and proximity to roadways (Brunekreef et al., 1997). Thus, emissions from diesel vehicles may contribute significantly to differences in $PM_{2.5}$ levels not only between urban and suburban communities in the NYC metropolitan region but also among neighborhoods within NYC.

The high concentration of diesel emissions sources in NYC neighborhoods such as Northern Manhattan and the South Bronx, the high burden of pediatric asthma prevalence and morbidity in these communities, and the strength of recent literature on impacts of traffic proximity and traffic-related airborne pollutants on respiratory symptoms and asthma in children (Gauderman et al., 2004; Kim et al., 2004; Miller et al., 2004; Ryan et al., 2007; Morgenstern et al., 2008) together provide a strong rationale for addressing this problem both through research and policy intervention. However, in the US, because DEP is not a regulated pollutant, its ambient concentrations are not routinely measured at small spatial scales. Although census tract-level DEP data have been modeled by the EPA as part of the National Air Toxics Assessment, these

estimates provide only a one-time assessment of annual average concentrations and are not amenable to time-series analyses in which acute health effects associated with DEP exposures over time are characterized. Furthermore, directly measured DEP concentrations at locations where populations spend large portions of their days may provide more accurate estimates of DEP exposures compared with data derived from dispersion models. The contribution of DEP to PM_{2.5} in the urban setting, combined with differences in spatial patterns for these two pollutants, points to a need for a more precise measure of exposure to DEP. This in turn, would enable better assessment of the extent to which DEP may be a key PM component driving higher risks of asthma and other respiratory exacerbations among urban residents.

Here we present and analyze PM_{2.5} and DEP exposure data from a study aimed at improving our understanding of the role of DEP in respiratory morbidity among adolescents residing and attending schools in the NYC metropolitan area. Recent evidence suggest that long-term exposures of children to traffic-related pollutants (Gauderman et al., 2004) and school-based exposures (Kim et al., 2004) are associated with impaired lung function growth and asthma prevalence, respectively. Thus, we examine the extent to which school proximity to diesel traffic sources may influence exposures of students by analyzing the spatial and temporal variations in continuously measured PM_{2.5} and black carbon (BC), measured at four school locations that differed in local traffic intensity and distance to highway. Atmospheric BC has multiple sources including incomplete fossil fuel and/or biomass combustion from mobile and stationary sources as well as abrasion of tires and brakes (Glaser et al., 2005). Because of the large contribution of BC from mobile sources, it is often used as a surrogate for traffic-related particles (Kim et al., 2004; Maciejczyk et al., 2004; deCastro et al., 2008). Measurement of BC with continuous monitors such as the aethalometer has shown good correlation with concentrations of DEP or with traffic counts (Wu et al., 2007; deCastro et al., 2008), which further supports its use as an indicator of DEP.

2. Methods

2.1 Sampling Design and Locations

Ambient air PM_{2.5} and BC were monitored at 4 high schools within the NYC metropolitan area, including 3 located in high-density NYC neighborhoods, and 1 located in a nearby suburb. Permission was obtained from the local Boards of Education as well as the Columbia University Medical Center Institutional Review Board prior to the start of the study. The New York City Board of Education granted permission on the condition that school identities and specific locations would not be disclosed in publications and presentations.

The 4 participating high schools were chosen to represent a range of distances to highways and local diesel traffic volumes. In 2003, monitoring was carried out at an urban school (U1) within 50 meters west of a highway. In 2004, monitoring was carried out at a second urban school (U2), located within 50 meters east of a highway with annual average daily traffic (AADT) 2.5 times higher than that at U1. In 2005, monitoring was conducted at a third urban school (U3), located within 50 meters south of a secondary street and more than 500 meters away from a highway with an AADT similar to that at U2 but that prohibits commercial traffic, including most diesel vehicles. The fourth school was located in a suburban town 20 kilometers northwest and generally upwind of the city. The suburban school was located more than 3 kilometers from a highway. The same suburban school was monitored concurrently with U1 and U2 to permit spatial urban vs. suburban comparisons. Measurements made at the suburban school in 2003 are referred to as S1, and measurements from 2004 are referred to as S2.

2.2 Ambient PM_{2.5} Monitoring

Ambient PM_{2.5} mass concentrations were monitored and recorded in 1-hour intervals at each school using a beta attenuation monitor (BAM, Model 1020, Met One Instruments Inc. Grant Pass, OR) placed in classroom windows (second or third floor) facing the adjacent roadway. A sharp cut cyclone in the BAM enables the sampling of only particles smaller than 2.5 μm at a 16.7 liters per minute (LPM) flow rate. The BAM operates on the principle that beta rays (electrons) are attenuated according to an exponential function of particulate mass when they pass through particles deposited on a filter tape. To correct for blank attenuation, the BAM first measures attenuation through an unexposed segment of filter tape. The tape is then exposed to ambient sample flow, accumulating a deposit. The blank-corrected attenuation readings are converted to mass concentrations. Data were downloaded weekly from a built-in data logger. Accuracy and precision were assessed by checking flow rates once per week. The detection limit of the BAM is approximately 4.8 $\mu\text{g}/\text{m}^3$ for a 1-hour average concentration.

2.3 Ambient Black Carbon Monitoring

Ambient BC was monitored continuously using a dual-beam aethalometer (Model AE-21, Magee Scientific, Berkeley, CA) placed in the same classroom windows as the BAM. A BGI cyclone on the inlet of the aethalometer is used to obtain a PM_{2.5} size cut, and suspended carbonaceous particles are deposited onto a quartz fiber tape at 4 LPM. Optical density (OD) or attenuation of a light beam caused by deposited elemental carbon is measured every 5 minutes at a wavelength of 880 nanometers. Differences in OD between measurements are multiplied by an absorption coefficient to convert OD to a mass concentration (Allen et al., 1999). Data were downloaded weekly from the built-in data logger to a disk. Accuracy and precision were assessed by checking flow rates once a week. Raw data were checked for aberrations and processed according to manufacturer's instructions. At the beginning and end of each monitoring year, the 2 aethalometers from simultaneously monitored schools were placed side by side in the laboratory to ensure consistency of measurement among instruments. The aethalometer has a detection limit of 0.1 $\mu\text{g}/\text{m}^3$ for a one-minute average.

2.4 Meteorological Monitoring

A weather station (Vantage Pro Model 6150C, Davis Instrument Corp., Hayward, CA) was installed on each school roof to monitor and record temperature, relative humidity, barometric pressure, wind speed, wind direction, and precipitation. The weather station was equipped with data logger and computer software interface (WeatherLink, Davis Instrument Corp., Hayward, CA) for storing, downloading and processing data. Hourly mixing height estimates were obtained from AERMET (American Meteorology/Environmental Protection Agency) modeling using twice daily mixing height measurements from Upton, NY and local hourly surface meteorological measurements obtained from the National Climatic Data Center at the National Oceanic and Atmospheric Administration.

2.5 Traffic Counting

At S1, traffic data were collected using Trax RD Automatic Traffic Recorder (Jamar Technologies Inc., Horsham, PA). This instrument collects traffic data using pneumatic tubes laid across the roadway. The recorded data were downloaded to a laptop computer and analyzed using Trax Pro traffic data analysis software. The vehicles are classified according to the Federal Highway Administration Scheme F, which separates vehicles into various classes based on the distance between axles and the number of axles. Data for each class were reported as counts/hour.

Because of costs and safety issues, traffic data were collected for the highway adjacent to U2 using a video camera. Data were collected by recording 3 minutes of digital video every 15

minutes with a webcam linked to a desktop computer. The video was collected from a window that had an oblique angle to the roadway adjacent to schools. Vehicles were counted manually by watching daytime videos and counting 1 out of 3 minutes of each video to obtain the number of gasoline powered vehicles (cars and light trucks). To improve counting statistics, all 3 minutes of each video was counted to obtain estimates for the number of diesel powered vehicles (trucks and buses). Vehicles were classified according to the Federal Highway Administration Scheme F. Data were averaged and linearly extrapolated to hourly traffic counts for hours that encompass the school day and have peak traffic volumes (6 am to 5 pm).

2.6 Statistical Analyses

Mean concentrations of PM_{2.5} or BC at simultaneously monitored schools were compared using non-parametric Kruskal-Wallis analysis of variance since BC and PM_{2.5} concentrations were non-normally distributed. Correlations between daily average BC or PM_{2.5} concentrations measured at pairs of simultaneously monitored schools were assessed using non-parametric Spearman's rank correlation. To account for autocorrelation among serial measurements of BC, associations of traffic volume and meteorological factors with hourly average BC concentrations were characterized using linear regression with autoregressive (AR) error terms (proc ARIMA in SAS) as previously described (deCastro et al., 2008). Wind direction was categorized into 4 groups: Northeast to Southeast (NE–SE, 45°–134°), Southeast to Southwest (SE–SW, 135°–224°), Southwest to Northwest (SW–NW, 225°–314°), and Northwest to Northeast (NW–NE, 315°–44°). Similar models were constructed to relate traffic counts with hourly PM_{2.5} concentrations. For relationships between each predictor and BC or PM_{2.5}, in plots of model predicted versus residuals, points were evenly distributed around the horizontal, indicating that all predictors met the assumptions for linear association. Statistical tests and modeling were performed using SAS 9.1.3 (Cary, NC, release 2005), and type I error rate (α) was set at 0.05 for all analyses. Significance in regression analyses with PM_{2.5} and BC was assessed using log-transformed data.

3. Results

3.1 Ambient PM_{2.5} concentrations at study schools

PM_{2.5} concentrations were measured during spring and early summer months at each school, although all schools were not monitored simultaneously because of limited sampling equipment. Significant urban to suburban differences in mean 24-hour average PM_{2.5} concentrations were observed. Overall mean PM_{2.5} concentrations at U2 were 1.8-fold higher than those at S2 ($p < 0.0001$) between March 11, 2004 and April 6, 2004 (Table 1), however, concentrations between schools were strongly correlated over time with a spearman's correlation coefficient of 0.906 ($p < 0.0001$) (data not shown). PM_{2.5} concentrations did not significantly vary among urban schools, and daily average concentrations of PM_{2.5} at U1 and U2 were nearly identical during the period when simultaneous measurements were available (May 15, 2003 and June 30, 2003). The lack of difference in PM_{2.5} measured at the 3 NYC schools may point to the large influence of weather and the importance of long range transport on PM_{2.5} concentrations in the Northeast U.S.

3.2 Ambient Black Carbon Concentrations

Mean (SD) BC concentrations were 2.3 (1.1) $\mu\text{g}/\text{m}^3$ for U1, 2.4 (1.2) $\mu\text{g}/\text{m}^3$ for U2, 1.4 (0.5) $\mu\text{g}/\text{m}^3$ for U3, 0.66 (0.37) $\mu\text{g}/\text{m}^3$ and 0.73 (0.61) $\mu\text{g}/\text{m}^3$ for S1 and S2, respectively (Table 1). Not all schools were monitored at the same time or during the same seasons, which may account for some of the differences in average BC concentrations since pollution mix varies season to season. Compared with the concurrent BC measurements from the suburban school, overall mean BC concentrations were 3.5-fold higher at U1 and 3.3-fold higher at U2 ($p < 0.0001$ for both between-school comparisons). These suburban-to-urban differences were larger than the

relative differences presented above for mean $PM_{2.5}$ concentrations and likely reflect the influence of local urban sources, including traffic, on air quality in NYC. As indicated in Figure 1, daily BC concentrations at urban schools were highly correlated with those at the suburban school ($r = 0.84$, $p < 0.0001$, U1 vs. S1; $r = 0.74$, $p < 0.0001$, U2 vs. S1). In regression models examining associations between weather variables and daily BC concentrations, daily average mixing height was significantly associated with changes in daily BC concentrations (data not shown), suggesting that day-to-day changes in BC at neighboring urban and suburban locations may be influenced by similar regional weather patterns. Consistently lower suburban levels may point to fewer sources of BC, including diesel vehicle traffic, relative to urban locations.

3.3 Influence of diesel and non-diesel traffic on BC and $PM_{2.5}$

To characterize the influence of local vehicle traffic on temporal variations in BC, hourly mean BC concentrations measured at U2 were regressed with hourly truck/bus or car counts measured between 6 am and 5 pm on the highway adjacent to U2 during the time period of March 12–18, March 20, and March 22, 2004. One lagged AR term (1 hour) was included in models to reduce serial autocorrelation among BC measurements; additional lags were not significant. The mean (SD) weekday rate of cars per hour between 6 am and 5 pm was 6025 (1250), and the mean (SD) rate of trucks/buses per hour was 626 (281).

At U2, an interquartile range (IQR) increase in trucks/buses per hour was associated with an increase of $0.62 \mu\text{g}/\text{m}^3$ ($p < 0.0001$) in 1-hour average BC, after adjusting for wind direction, average wind speed, humidity, average temperature, mixing height, and hourly car counts (Table 2). Car traffic counts were not associated with hourly BC concentrations. Wind speed and wind direction had the largest magnitude of effect on BC concentrations at U2. Winds from the NE to SE quadrant, which transport highway pollution away from U2, were associated with significant decreases in BC. Winds from the SW to NW quadrant, which would transport highway emissions towards the school, were not associated with increases in BC. At S1, between May 30 and June 15, 2003, the mean (SD) rate of cars was 339 (104) per hour. The mean (SD) rate of trucks and buses was 49 (35) per hour. Inclusion of 3 lagged AR terms (3 hours) reduced serial autocorrelation among BC measurements. At S1, an IQR increase of 70.5 trucks and buses per hour was associated with a significant increase of $0.20 \mu\text{g}/\text{m}^3$ BC ($p = 0.009$), after controlling for weather and hourly car counts (Table 2). Car traffic counts were not associated with hourly BC concentrations.

The relative influences of weather and traffic on BC were evaluated by comparing goodness of fit of models that included only weather or only traffic variables. For U2, a model that included only weather variables had an Akaike's information criterion (AIC) of 41.89, whereas a model that included only traffic variables had an AIC of 77.64, indicating that the first model with weather variables fit the data better. At S2, a model that included only weather variables had an AIC of 130.50, whereas a model that included only traffic variables had an AIC of 242.20, indicating that for S2, the first model with weather variables fit the data better. For both U2 and S1, models that included both weather and traffic variables had the best fit.

At U2, hourly truck/bus counts and meteorological variables, including wind direction, wind speed, and humidity were significantly associated with hourly $PM_{2.5}$ concentrations (Table 3). AR terms were not significant and not included in models. At U2, an IQR increase of 443 trucks/buses per hour was associated with a $3.0 \mu\text{g}/\text{m}^3$ ($p = 0.04$) increase in $PM_{2.5}$ concentrations. Hourly car counts were not associated with hourly $PM_{2.5}$ concentrations.

4. Discussion

To investigate the influence of diesel traffic on ambient PM concentrations, we monitored $PM_{2.5}$ and BC, a DEP indicator, at 3 schools in NYC and 1 suburban school in the NYC

metropolitan area. BC concentrations were higher at urban schools compared with the suburban school; among the 3 urban schools, BC concentrations were higher at the 2 schools located adjacent to highways. The hourly average rate of diesel traffic was a significant predictor of hourly average ambient BC and PM_{2.5} concentrations. Hourly average rate of non-diesel vehicles was not associated significantly with BC or PM_{2.5}. These results suggest that diesel vehicle traffic may be important local sources of airborne fine particles in dense urban areas and in suburban areas.

Urban-suburban differences in BC were larger than urban-suburban differences in PM_{2.5}, which is consistent with prior NYC studies (Kinney et al., 2005), and point to the greater spatial heterogeneity in BC, compared with PM_{2.5}. U1 and U2, which were located within 50 meters of highways, had higher mean BC concentrations than U3, which was located 500 meters from a highway. These latter results are similar to those from a study in Netherlands that measured higher concentrations of black smoke in schools 47–377 meters from a freeway, compared with schools greater than 400 meters from a highway (Brunekreef et al., 1997).

Although urban BC concentrations were significantly higher than suburban concentrations, daily variations in BC were highly correlated at simultaneously monitored urban and suburban schools. Weather factors were significant predictors of daily variations in BC at a NYC school (wind speed, wind direction, and mixing height) and at the suburban school (wind speed, humidity, and mixing height). Therefore, temporal correlation between locations may be explained by similar daily weather patterns and mixing heights that exist over the greater New York City metropolitan area, which includes surrounding suburban counties. At all schools, daily BC and PM_{2.5} concentrations were strongly correlated over time, which was expected since BC is a component of PM_{2.5}. The high degree of correlation between BC and PM_{2.5} also reflects common influence of weather on daily concentrations.

In spite of 2.5-fold higher local traffic volume at U2, mean BC concentrations at U1 and U2 were similar, which conflicts with previous observations showing a range in BC concentrations of 2.2–9.4 µg/m³ measured by a mobile van at the roadside across several sites in the South Bronx (Maciejczyk et al., 2004) and studies showing strong diesel traffic impacts on black carbon concentrations measured on sidewalks in the South Bronx (Lena et al., 2002) and Harlem (Kinney et al., 2000). Lack of difference in BC between U1 and U2 may be attributed to contrasting patterns of wind direction and wind speed. At U1, 18% days had winds from the NE to SE quadrant, which would transport highway emissions towards the school. These winds were associated with the slowest wind speeds (1.1 m/s) and highest mean BC concentration (3.5 µg/m³), compared with winds from other directions. In contrast, U2 had a smaller proportion of days (11%) with winds from the direction of the highway (SW to NW quadrant). Furthermore, winds from this direction were associated with the fastest wind speeds (4.0 m/s) and the lowest mean BC concentrations (1.6 µg/m³), which was likely due to greater dispersion of highway traffic emissions. Winds from the NE to SE quadrant, which would transport highway emission away from U2, comprised 37% of days and were associated with the slowest wind speeds (1.5 m/s). Thus, in heavy traffic areas, traffic volume as well as local meteorology may influence exposures to traffic-related pollutants.

Despite the varied geometry of urban school 2 and the suburban school locations and patterns of wind direction and wind speed at schools, diesel vehicles had a significant influence on ambient BC concentrations at both schools. At U2, increases in the rate of trucks/buses also were significantly associated with increases in PM_{2.5}. Nondiesel vehicles did not significantly influence BC or PM_{2.5} concentrations at the urban school, and these findings are consistent with observations that particle emission rates are higher among diesel vehicles than among non-diesel vehicles (Zielinska et al., 2004; Ban-Weiss et al., 2008). Hourly mixing height estimates were significantly associated with hourly changes in BC at the suburban school but

not at the urban school. At U2, traffic and complex interactions between wind speed and wind direction may have been more important influences on BC at shorter time scales. These results, nonetheless, support the hypothesis that local variations due to diesel traffic are important contributors to spatial differences in BC and also may account for variations in $PM_{2.5}$ observed on small scales. The significant impact of diesel traffic on $PM_{2.5}$ may be due to increases in emissions-related particles as well as resuspension of road dust. A recent study in Baltimore also observed a significant effect of vehicle counts on BC concentrations, although the effects of diesel and non-diesel vehicles were not evaluated separately (deCastro et al., 2008). The present study provides additional evidence that diesel vehicles but not gasoline powered vehicles significantly influence BC concentrations.

In previous studies in the South Bronx, truck volume explained a large portion ($R^2 = 0.84$) of the variation in EC measured at multiple sites in the South Bronx (Lena et al., 2002). Although R^2 estimates were not available for the models used in the present study, weather variables were found to fit the data better than traffic variables. Discrepancy between the present and the aforementioned study may be explained by measurement of BC more than 30 meters from roadways in the current study vs. sidewalk measurements in the previous study. At these distances, BC concentrations may be influenced significantly by mixing forces such as atmospheric turbulence more so than BC concentrations measured adjacent to roadways (Zhang and Wexler 2004). Additionally, U2 is located in an open area with a river on the other side of the highway, which may contribute to the complex interactions between wind direction and wind speed that decrease the contribution of highway emissions to BC measured at the school. In the current analyses, an indicator for stalled traffic or duration of stagnant traffic on highways was not included in regression models. Stagnant traffic releases greater emissions than running traffic (Zhu et al., 2002), and therefore, the inclusion of a metric that describes stalled traffic, which occurs frequently on the highway proximal to U2, may increase the magnitude of effect of hourly diesel traffic counts on hourly BC concentrations.

This study makes an important contribution to the literature because of its extensive spatially- and time-resolved measurements of BC, a commonly used indicator of DEP, which permitted spatial comparisons of $PM_{2.5}$ and BC and allowed analyses of the effect of the rate of diesel and non-diesel traffic on particle concentrations. These results suggest that specific locations such as schools that are located close to highways may be an important source of repeated exposure of children to elevated concentrations of traffic-related PM for 7–8 hours per day. An important implication of these findings is that central site $PM_{2.5}$ concentrations may be inadequate for evaluating particle air quality at urban school locations, particularly for health-relevant PM components such as BC. While central site measurements may provide reasonable estimates of exposure in time-series studies of acute health effects because of high correlations with school-based measurements, they may result in exposure misclassification in studies that examine differences in exposures and health effects among subjects living different neighborhoods. The findings of the current study provide support for increased monitoring of traffic-related $PM_{2.5}$ components at neighborhood-level geographic scales and for studying the respiratory health effects in association with these traffic-related PM, which may be significantly contributing to higher asthma prevalence and asthma exacerbations in communities with higher concentrations of traffic-related PM.

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References

- Allen GA, Lawrence J, Koutrakis P. Field validation of a semi-continuous method for aerosol black carbon (aethalometer) and temporal patterns of summertime hourly black carbon measurements in southwestern PA. *Atmospheric Environment* 1999;33:817–823.
- Ban-Weiss GA, MCLAughlin JP, Harley RA, Lunden MM, Kirchstetter TW, Kean AJ, Strawa AW, Stevenson ED, Kendall GR. Long-term changes in emissions of nitrogen oxides and particulate matter from on-road gasoline and diesel vehicles. *Atmospheric Environment* 2008;42:220–232.
- Brunekreef B, Janssen NAH, de Hartog J, Harssema H, Knape M, van Vliet P. Air Pollution from Truck Traffic and Lung Function in Children Living near Motorways. *Epidemiology* 1997;8:298. [PubMed: 9115026]
- deCastro BR, Wang L, Mihalic JN, Breyse PN, Geyh AS. The Longitudinal Dependence of Black Carbon Concentration on Traffic Volume in an Urban Environment. *Journal of Air and Waste Management Association* 2008;58:928–393.
- EPA (United States Environmental Protection Agency). Criteria Pollutants - Metropolitan Statistical Area Air Quality Trends, 1993-2002. 2004. Table A-16
- EPA. Air Quality Designations and Classifications for the Fine Particles (PM_{2.5}) National Ambient Air Quality Standards. 2005.
- Fraser MP, Buzcu B, Yue ZW, McGaughey GR, Desai NR, Allen DT, Seila RL, Lonneman WA, Harley RA. Separation of fine particulate matter emitted from gasoline and diesel vehicles using chemical mass balancing techniques. *Environmental and Science Technology* 2003;37:3904–3409.
- Garg, R.; Karpati, A.; Leighton, J.; Perrin, M.; Shah, M. Asthma Facts. Second Addition. New York City Department of Health and Mental Hygiene; 2003.
<http://www.nyc.gov/html/doh/downloads/pdf/asthma/facts.pdf>
- Gauderman WJ, Avol E, Gilliland F, Vora H, Thomas D, Berhane K, McConnell R, Kuenzli N, Lurmann F, Rappaport E, Margolis H, Bates D, Peters J. The Effect of Air Pollution on Lung Development from 10 to 18 Years of Age. *New England Journal of Medicine* 2004;351:1057–1067. [PubMed: 15356303]
- Glaser B, Dreyer A, Bock M, Fiedler S, Mehring M, Heitmann T. Source apportionment of organic pollutants of a highway-traffic-influenced urban area in Bayreuth (Germany) using biomarker and stable carbon isotope signatures. *Environmental and Science Technology* 2005;39:3911–3917.
- Kim JJ, Smorodinsky S, Lipsett M, Singer BC, Hodgson AT, Ostro B. Traffic-related Air Pollution near Busy Roads: The East Bay Children's Respiratory Health Study. *American Journal of Respiratory and Critical Care Medicine* 2004;170:520–526. [PubMed: 15184208]
- Kinney PL, Aggarwal M, Northridge ME, Janssen NAH, Shepard P. Airborne Concentrations of PM_{2.5} and Diesel Exhaust Particles on Harlem Sidewalks: A Community-Based Pilot Study. *Environmental Health Perspectives* 2000;108:213–218. [PubMed: 10706526]
- Kinney, PL.; Chillrud, SN.; Sax, S.; Ross, JM.; Pederson, DC.; Johnson, D.; Aggarwal, M.; Spengler, JD. Toxic Exposure Assessment: A Columbia-Harvard (TEACH) Study (The New York City Report). Mickey Leland NUATRC; 2005. Research Report No. 3
- Koenig JQ, Jansen K, Mar TF, Lumley T, Kaufman J, Trenga CA, Sullivan J, Liu L-JS, Shapiro GG, Larson TV. Measurement of Offline Exhaled Nitric Oxide in a Study of Community Exposure to Air Pollution. *Environmental Health Perspectives* 2003;111:1265–1629. [PubMed: 12842784]
- Laden F, Neas LM, Dockery DW, Schwartz J. Association of Fine Particulate Matter from Different Sources with Daily Mortality in Six U.S. Cities. *Environmental Health Perspectives* 2000;108:941–947. [PubMed: 11049813]
- Lena TS, Ochieng V, Carter M, Holguin-Veras J, Kinney PL. Elemental Carbon and PM_{2.5} Levels in an Urban Community Heavily Impacted by Truck Traffic. *Environmental Health Perspectives* 2002;110:1009–1015. [PubMed: 12361926]
- Maciejczyk PB, Offenberger JH, Clemente J, Blaustein M, Thurston GD, Chi Chen L. Ambient pollutant concentrations measured by a mobile laboratory in South Bronx, NY. *Atmospheric Environment* 2004;38:5283–5294.
- Miller RL, Garfinkel R, Horton M, Camann D, Perera FP, Whyatt RM, Kinney PL. Polycyclic Aromatic Hydrocarbons, Environmental Tobacco Smoke, and Respiratory Symptoms in an Inner-city Birth Cohort. *Chest* 2004;126:1071–1078. [PubMed: 15486366]

- Morgenstern V, Zutavern A, Cyrys J, Brockow I, Koletzko S, Kramer U, Behrendt H, Herbarth O, von Berg A, Bauer CP, Wichmann HE, Heinrich J, the GINI Study Group; the LISA Study Group. Atopic Diseases, Allergic Sensitization, and Exposure to Traffic-related Air Pollution in Children. *American Journal of Respiratory and Critical Care Medicine* 2008;177(12):1331–1337. [PubMed: 18337595]
- Norris G, YoungPong SN, Koenig JQ, Larson TV, Sheppard L, Stout JW. An Association between Fine Particles and Asthma Emergency Department Visits for Children in Seattle. *Environmental Health Perspectives* 1999;107:489–493. [PubMed: 10339450]
- (NRC) National Research Council. Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience - Special Report 264. National Academy Press; Washington, D.C.: 2002.
- O'Connor GT, Neas L, Vaughn B, Kattan M, Mitchell H, Crain EF, Evans Iii R, Gruchalla R, Morgan W, Stout J, Adams GK, Lippmann M. Acute respiratory health effects of air pollution on children with asthma in US inner cities. *Journal of Allergy and Clinical Immunology* 2008;121:1133–1139. [PubMed: 18405952]
- Ryan PH, Lemasters GK, Biswas P, Levin L, Lindsey M, Bernstein DI, Lockey J, Villareal M, K. KHG, Grinshpun SA. A comparison of proximity and land use regression traffic exposure models and wheezing in infants. *Environmental Health Perspectives* 2007;115:278–284. [PubMed: 17384778]
- (SPARCS) Statewide Planning and Research Cooperative System. New York State Asthma Surveillance Summary Report. New York State Department of Health; 2007.
http://www.nyhealth.gov/statistics/ny_asthma/pdf/2007_asthma_surveillance_summary_report.pdf
- Wu, C.-f.; Larson, TV.; Wu, S.-y.; Williamson, J.; Westberg, HH.; Liu, LJS. Source apportionment of PM_{2.5} and selected hazardous air pollutants in Seattle. *Science of The Total Environment* 2007;386:42–52. [PubMed: 17716709]
- Zhang KM, Wexler AS. Evolution of particle number distribution near roadways--Part I: analysis of aerosol dynamics and its implications for engine emission measurement. *Atmospheric Environment* 2004;38:6643–6653.
- Zhu Y, Hinds WC, Kim S, Shen S, Sioutas C. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment* 2002;36:4323–4335.
- Zielinska B, Sagebiel J, McDonald JD, Whitney K, Lawson DR. Emission Rates and Comparative Chemical Composition from Selected In-Use Diesel and Gasoline-Fueled Vehicles. *Journal of Air and Waste Management Association* 2004;54:1138–1150.

Figure 1.

Temporal trends in daily average black carbon concentrations (BC) measured at urban and suburban schools

a. Urban School 1 (U1) and the Suburban School (S1) - 5/6/03–6/8/03. Compared with S1, mean of 24-hour average BC concentrations were 3.6-fold higher at U1, although concentrations were significantly correlated over time ($r = 0.74$, $p < 0.0001$).

b. Urban School 2 (U2) and the Suburban School (S2) - 2/23/04–3/28/04. Compared with S2, mean of 24-hour average BC concentrations were 3.2-fold higher at U2, although concentrations were significantly correlated over time (0.84, $p<0.0001$).

Table 1
Means and distributions of 24-hour average PM_{2.5} and black carbon (BC) concentrations measured at study schools

School ^a	Location	Pollutant	Monitoring Dates	Mean (SD)	Minimum	Median	Maximum
U1	Urban, Medium-sized Highway	PM _{2.5}	4/1/03–6/30/03	21.2 (11.8)	2.1	18.4	75.0
		BC	5/5/03–6/7/03	2.3 (1.1)	0.68	2.4	5.5
U2	Urban, Large Highway	PM _{2.5}	5/15/03–6/30/03, 3/11/04–6/21/04	24.7 (12.3)	6.6	21.9	75.0
		BC	2/23/04–3/28/04	2.4 (1.2)	0.57	2.0	4.9
U3	Urban, Secondary Street	PM _{2.5}	3/24/05–5/28/05	24.5 (8.4)	11.5	23.1	49
		BC	4/2/05–5/19/05	1.4 (0.48)	0.33	1.5	2.3
S1	Suburban	PM _{2.5}	None				
		BC	5/6/03–6/7/03	0.66 (0.37)	0.11	0.60	1.8
S2	Suburban	PM _{2.5}	3/11/04–6/30/04	13.8 (9.2)	1.0	12.0	41.3
		BC	2/23/04–3/28/04	0.73 (0.61)	0.10	0.49	2.7

^aU1 = Urban School 1, U2 = Urban School 2, U3 = Urban School 3, S1 = Suburban School 2003 measurements, S2 = Suburban School 2004 measurements

Table 2

Effect of hourly traffic and weather on black carbon concentrations at U2 and S1

Variable (Interquartile range increase)		Beta Estimate ^a (p-value)	
		U2 ^b	S1 ^b
Trucks/Buses		0.62 (0.003)	0.20 (0.0009)
		per 443/hr increase	per 70.5/hr increase
Cars		0.19 (0.17)	0.07 (0.42)
		per 1895/hr increase	per 479/hr increase
Wind Direction	NW to NE	Reference	Reference
	NE to SE	-1.29 (0.0008)	-0.22 (0.04)
(S2 downwind of highway)	SE to SW	-0.09 (0.83)	0.21 (0.13)
(U2 downwind of roadway)	SW to NW	0.48 (0.25)	0.15 (0.10)
Wind Speed		-1.67 (<0.0001)	-0.12 (0.0009)
		per 3.4m/s increase	per 1.5 m/s increase
Humidity		0.04 (0.31)	0.29 (0.0009)
		per 50.8% increase	per 26% increase
Temperature		-0.26 (0.273)	0.22 (0.007)
		per 5.1°C increase	per 5.5°C increase
Mixing Height		-1.75 (0.51)	-0.14 (0.003)
		per 354 m increase	per 479 m increase

^aDescribes change in concentration of BC ($\mu\text{g}/\text{m}^3$) per interquartile range increase in dependent variable, adjusted for other variables in the model.

^bU2 = Urban School 2, S1 = Suburban School 2003 measurements.

^cVariables significantly associated with changes in BC ($p < 0.05$) are in bold.

Table 3Effect of hourly traffic and weather on PM_{2.5} concentrations at U2

Variable		Beta Estimate ^a (p-value)
Trucks/Buses (443/hr increase)		3.0 (0.04)
Cars (1895/hr increase)		1.3 (0.24)
Wind Direction	NW to NE	Reference
	NE to SE	-15.5 (<0.0001)
	SE to SW	1.3 (0.73)
	SW to NW	6.4 (0.03)
(U2 downwind of roadway)		
Wind Speed (3.4 m/s increase)		-9.8 (<0.0001)
Humidity (50.8% increase)		8.0 (0.003)
Temperature (5.1°C increase)		-0.63 (0.56)
Mixing Height (354 m increase)		-1.5 (0.10)

^aDescribes change in concentration of PM_{2.5} (µg/m³) per interquartile range increase in dependent variable, adjusted for other variables in the model.

^bVariables significantly associated with changes in PM_{2.5} (p<0.05) are in bold.