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Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway

Allison P. Patton[*,a,1], **Jessica Perkins**[a], **Wig Zamore**[b], **Jonathan I. Levy**[c], **Doug Brugge**[d], and **John L. Durant**[a]

[a]Civil and Environmental Engineering, Tufts University, 200 College Ave, Medford, MA 02155, USA

[b]Somerville Transportation Equity Partnership, Somerville, MA, USA

[c]Boston University School of Public Health, 715 Albany St, Boston, MA 02118, USA

[d]Public Health and Community Medicine, Tufts University, 136 Harrison Avenue, Boston, MA 02111, USA

Abstract

Relatively few studies have characterized differences in intra- and inter-neighborhood traffic-related air pollutant (TRAP) concentrations and distance-decay gradients in along an urban highway for the purposes of exposure assessment. The goal of this work was to determine the extent to which intra- and inter-neighborhood differences in TRAP concentrations can be explained by traffic and meteorology in three pairs of neighborhoods along Interstate 93 (I-93) in the metropolitan Boston area (USA). We measured distance-decay gradients of seven TRAPs (PNC, pPAH, NO, NO_X, BC, CO, $PM_{2.5}$) in near-highway (<400 m) and background areas (>1 km) in Somerville, Dorchester/South Boston, Chinatown and Malden to determine whether (1) spatial patterns in concentrations and inter-pollutant correlations differ between neighborhoods, and (2) variation within and between neighborhoods can be explained by traffic and meteorology. The neighborhoods ranged in area from 0.5 to 2.3 km^2. Mobile monitoring was performed over the course of one year in each pair of neighborhoods (one pair of neighborhoods per year in three successive years; 35-47 days of monitoring in each neighborhood). Pollutant levels generally increased with highway proximity, consistent with I-93 being a major source of TRAP; however, the slope and extent of the distance-decay gradients varied by neighborhood as well as by pollutant, season and time of day. Correlations among pollutants differed between neighborhoods (e.g., ρ = 0.35-0.80 between PNC and NO_X and ρ = 0.11-0.60 between PNC and BC) and were generally lower in Dorchester/South Boston than in the other neighborhoods. We found that the generalizability of near-road gradients and near-highway/urban background contrasts was limited

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[*] Corresponding Author 170 Frelinghuysen Road Piscataway, NJ 08854, USA patton@eohsi.rutgers.edu Phone: +1 617 627-3211 Fax: +1 617 627-3994.

[1] Present Address: Environmental and Occupational Health Sciences Institute, Rutgers University, 170 Frelinghuysen Road, Piscataway, NJ 08854, USA

for near-highway neighborhoods in a metropolitan area with substantial local street traffic. Our findings illustrate the importance of measuring gradients of multiple pollutants under different ambient conditions in individual near-highway neighborhoods for health studies involving inter-neighborhood comparisons.

Keywords

near-highway; distance-decay gradients; mobile monitoring; traffic-related air pollution; metropolitan Boston (USA)

1. Introduction

Living near major roadways is associated with increased risks of cardiovascular and pulmonary disease (Gan et al., 2009; Hoek et al., 2013; McConnell et al., 2010). The possibility that exposure to traffic-related air pollution (TRAP) may play a role has motivated research to understand which, if any, of the many components of TRAP may be causative agents (Brugge et al., 2007; HEI, 2010).

Disentangling the effects of TRAP components in health studies requires an understanding of how pollutants are patterned in space and time, and the extent to which patterns differ by pollutant and across geographic settings. TRAP concentrations can vary significantly in both space and time near roadways (Karner et al., 2010; Levy et al., 2013). Sharp decreases in the concentration of many pollutants including elemental carbon (EC), black carbon (BC), carbon monoxide (CO), nitrogen oxides (NO_X), particle number (PNC), and volatile organic compounds have been measured within 150 – 650 m of the edges of highways and major roads (Durant et al., 2010; Karner et al., 2010; Padró-Martínez et al., 2012; Pattinson et al., 2014; Roorda-Knape et al., 1998). The most-pronounced gradients occur for more reactive pollutants with low background concentrations, such as NO and ultrafine particles (UFP; <100 nm in diameter), and the least-pronounced gradients occur for relatively inert pollutants with elevated background concentrations (e.g., fine particle mass)(Zhou and Levy, 2007). In urban areas, spatial characterization can be complicated by street canyons and roadside structures such as noise barriers, elevated or depressed roadways, and buffers of trees and shrubs (Hagler et al., 2012; Hagler et al., 2010; Ning et al., 2010; Vardoulakis et al., 2003). Studies suggest that roadside structures tend to decrease near-road TRAP concentrations and increase on-road concentrations (Finn et al., 2010; Hagler et al., 2012; Ning et al., 2010; Steffens et al., 2014).

While previous efforts have focused on TRAP variation between cities (Eeftens et al., 2012; Fruin et al., 2014; Lebret et al., 2000) and within cities (Clougherty et al., 2008; Dons et al., 2013; Duvall et al., 2012; Jerrett et al., 2005; Levy et al., 2014), there are relatively few reports on the extent to which TRAP concentrations and spatial distributions measured in one near-highway neighborhood can be generalized to other neighborhoods along the same highway. Studies are needed that characterize TRAP variation at fine scales – e.g., <~5 km^2 neighborhoods – for the purpose of developing accurate estimates of TRAP exposures in urban populations. Because spatial distributions of TRAP are also affected by factors that vary by season or time of day (such as wind patterns, temperature, and emissions source strength)(Kassomenos et al., 2014; Levy et al., 2013), measurement campaigns aimed at characterizing spatial differences in near-highway TRAP in neighborhoods should be performed over time. One way to measure differences in TRAP distance-decay gradients and temporal trends near highways is to conduct mobile monitoring along a highway in a single urban area in different seasons and times of day.

The goal of our study was to characterize gradients of seven TRAPs (PNC, pPAH, NO, NO_X, BC, CO, $PM_{2.5}$) in three near-highway (<400 m) and three background (>1000 m from nearest interstate highway) urban neighborhoods in the metropolitan Boston area (Massachusetts, United States). Our specific objectives were to determine whether (1) spatial patterns in concentrations and inter-pollutant correlations differ between neighborhoods, and (2) variation within and between neighborhoods can be explained by traffic and meteorology. We hypothesized that for each study area TRAP concentrations would be higher near highways than in urban background areas, and that pollutant distance-decay gradients could be explained in terms of traffic and meteorology. In particular, we expected that gradients would be similar in neighborhoods with single highways compared to neighborhoods with multiple major roadways and tall buildings, and that TRAP concentrations and the composition of TRAP mixtures would change in response to temporally-variable forcings. This work was performed as part of the Community Assessment of Freeway Exposure and Health study (CAFEH), a community-based participatory research (CBPR) study of TRAP exposure and cardiovascular health risk (Fuller et al., 2013).

2. Material and Methods

2.1. Study Area Descriptions

TRAP concentrations were measured in three demographically-matched pairs of near-highway (NH) and urban background (UB) neighborhoods in the Boston metropolitan area: Somerville (NH and UB), Dorchester/South Boston (NH and UB), Chinatown (NH) and Malden (UB; Figure 1). Study areas were relatively small, ranging in size from 0.5 km^2 (Chinatown) to 2.3 km^2 (Somerville; Table 1). Near-highway neighborhoods were defined as being 0-400 m from the nearest edge of Interstate 93 (I-93), which carries an average daily traffic (ADT) load of $1.5x10^5$ vehicles per day (vpd; Central Transportation Planning Staff, 2012). Diesel vehicles accounted for 3.8% of I-93 traffic and <5% of traffic on local roads (Callahan, 2012; McGahan et al., 2001).

Mobile monitoring in all three pairs of neighborhoods was conducted over the course of a year (Table 2; Figure S1). Monitoring was conducted in Somerville (Figures 1A and 1B) from September 2009 to August 2010. Somerville air pollution sources were dominated by major roadways, including I-93, state highways, and a collector road. Route-38 (Mystic Avenue, ADT = 30,000 vpd), a four-lane state highway adjacent to I-93 in Somerville, was defined as part of the I-93 highway corridor (Central Transportation Planning Staff, 2012). Monitoring was conducted in Dorchester and South Boston, herein referred to as “Dorchester” (Figures 1C and 1D), from September 2010 to July 2011. In this area, I-93 runs parallel to railroad lines about 3 m to 6 m below grade. Monitoring in Chinatown (Figure 1E) and Malden (Figure 1F) was performed between August 2011 and July 2012.

Chinatown is located in downtown Boston and contains many major roadways and street canyons. The neighborhood is also near South Station, a regional transportation hub for trains and buses. Chinatown is flanked on its east side by I-93 and bisected east to west by I-90 (~90,000 vpd; Central Transportation Planning Staff, 2012). A residential neighborhood in Malden with similar demographics was selected as the background area to pair with Chinatown because all of Chinatown was <400 m from I-93. The Malden study area contains a diesel bus terminal and two commuter rail stations. More details on key features of each study area are available in Table 1 and Supporting Information (SI) Section 2.

2.2. Data Collection

Mobile monitoring was conducted with the Tufts Mobile Air Pollution Monitoring Laboratory (TAPL), a gasoline-powered vehicle that was driven on fixed routes (not on I-93) in each neighborhood (Figure 1; details in SI 2 and Padró-Martínez et al., 2012). Each route took 40-60 minutes to complete and was driven in 2-6 hour shifts on each day of monitoring. Monitoring was conducted on 35-47 days (85-281 hours) in each neighborhood in the morning, afternoon, and evening in winter, spring, summer, and fall on non-consecutive days selected to maximize variability in meteorological and traffic conditions (Table 2, Table S1). In Somerville and Dorchester, the near-highway and urban background areas were close enough that they could be monitored on the same day; however, Chinatown (near-highway) and Malden (background) were too far apart to monitor both neighborhoods on the same day (11 km), so monitoring in these two neighborhoods was conducted up to 8 days apart (mean difference = 2 days). The TAPL measured PNC, NO, NO_X, CO, BC, particle-bound polycyclic aromatic hydrocarbons (pPAH), and fine particulate mass ($PM_{2.5}$; Table S2). Measurement averaging times ranged from 1-s (PNC) to 60-s (BC) and the distance between measurements was 5-600 m. Quality control measures included side-by-side instrument comparisons, flow checks, and lag-time corrections. To avoid inclusion of measurements tainted by self-sampling of exhaust from the TAPL, data were censored for TAPL speeds <5 km/h (~14% of data was censored). In Chinatown, correction of the GPS coordinates was sometimes necessary due to weak satellite signals in street canyons.

Meteorological, traffic, and geographical data were obtained from public datasets and assigned to each pollutant measurement using SAS 9.2 (see Figure 1 for site locations). Wind speed and direction (7.9 m above ground level) and temperature (2 m above ground level) data were measured at Logan International Airport (NCDC, 2012). This meteorological station was selected because of high data completeness across all three years of monitoring (~99%), and it provides a better estimate of regional meteorology than of local meteorology, especially in the case of Chinatown where there are many street canyons. Hourly highway traffic counts and speed were measured by the Massachusetts Department of Transportation using remote traffic microwave sensors (model X3; stakeholder.traffic.com). Distance to highway edge was obtained by conducting spatial joins of measurement locations with a highway polygon in ArcGIS (Lane et al., 2013).

2.3. Data Analysis

To determine whether monitoring in the three study areas in different years impacted our results, we compared hourly measurements of CO, NO, and NO_X and daily measurements of

$PM_{2.5}$ collected continuously throughout the 3-year study period at the EPA Speciation Trends Network site (EPA-STN; ID: 25-025-0042) in Boston. This site is located ~1,500 m west of I-93 and in a mixed residential and commercial area (Figure 1; MA DEP, 2012). Interannual differences in CO, NO, NO_X, and $PM_{2.5}$ between September 2009 and July 2012 were tested using a multiple comparison Kruskal-Wallace test at the 95% confidence level (Giraudoux, 2013; Graves et al., 2012). To test for potential bias due to monitoring on different days in Chinatown and Malden, NO, NO_X, and CO measurements collected at the EPA-STN site during the hours of monitoring in the two neighborhoods were compared using the Kruskal-Wallace tests at the 95% confidence interval. $PM_{2.5}$ data were only available for every third day and were therefore not included in the analysis comparing monitoring days in Chinatown and Malden.

The one-sided Wilcoxon rank sum test (95% CI) was used to determine whether near-highway pollutant concentrations were statistically higher than concentrations in the paired urban background area. Spatial gradients in the near-highway areas were visualized with loess smoothing windows (spans) between 0.10 and 0.75. The spans with the least smoothing (smallest span) that had little noise were presented with 95% confidence intervals from generalized additive models (GAMs; Hastie, 2013). Smooths are presented instead of scatterplots because the large number of points (>160,000 per study area) interferes with scatterplot readability and interpretability.

The effects of temporal factors including meteorology and traffic volume on air pollutant concentrations were explored using several visualization tools. Loess smooths and boxplots were used to explore the impacts of individual factors like temperature and wind speed. Polar plots were used to explore the joint effects of wind speed and wind direction on pollutant concentrations (Carslaw and Ropkins, 2012).

Spearman correlations were calculated between hourly median pollutant concentrations in each near-highway and urban background area to reduce the impact of individual spikes. Spearman correlations were also generated for different times of the day as well as for different seasons. These correlations may change over short time periods due to differences between fresh and aged pollutants; therefore, the sensitivity of correlations to aggregation time was tested by comparing Spearman correlations for hourly medians with those for monthly, daily, and 1-minute medians for a subset of the data. The 1-min aggregation time matched the resolution of the BC monitor, which had the longest reporting interval of all the monitors. All statistical analyses were performed in R (R Core Team, 2013).

3. Results

3.1. Effects of Non-simultaneous Monitoring

Differences related to non-simultaneous monitoring as measured at the EPA-STN site in Boston were small or statistically insignificant; therefore, we did not adjust our measurements to reflect the non-simultaneous measurement periods. Interannual differences in median NO, NO_X, CO, and $PM_{2.5}$ concentrations measured at the EPA-STN site were low: <2 ppb, <2 ppb, <5 ppb, and <0.1 $\mu g/m^3$, respectively (Figure 2). $PM_{2.5}$ was statistically the same across all three years (Kruskal-Wallace multiple comparisons, $p=0.89$).

There was also no statistical difference between NO_X in the first two years or CO in the second two years ($p>0.05$ for all). Trends in concentrations of CO, NO, and NO_X were not expected to affect the comparison among neighborhoods (all changed at a rate of <3 ppb/year; $p<0.001$), and there was no statistically significant trend in $PM_{2.5}$ ($p>0.99$). In comparing NO, NO_X, and CO concentrations at the EPA-STN site during the hours of non-simultaneous monitoring in Chinatown and Malden, there was no significant difference in NO or NO_X (Kruskal-Wallace multiple comparisons, $p = 0.23$ and 0.87, respectively); however, CO concentrations were higher during monitoring in Malden ($p=0.03$; Figure S2). The median CO concentrations measured at the EPA-STN site were 232.6 ppb during the hours of monitoring in Chinatown and 265.0 ppb during the hours of monitoring in Malden. This difference suggests there may have been some bias in the CO results: as much as 25% of the difference between Malden and Chinatown CO (Table 3) can be attributed to monitoring on different days in the two neighborhoods.

3.2. Spatial Differences

Near highway – urban background contrasts were not the same for all pollutants in all neighborhoods. In Somerville and Chinatown, concentrations of all seven pollutants were higher near I-93 compared to urban background; however, in Dorchester only PNC, pPAH, and BC were higher near I-93 compared to background (Wilcoxon rank sum test, $p<0.001$) (Table 3; Figure 3). In Dorchester the median concentrations of NO_X and NO were not statistically different near I-93 compared to background, and median concentrations of CO and $PM_{2.5}$ were actually higher in the background area than near the highway. The highest concentrations of gaseous pollutants in Dorchester tended to occur when winds were from the west (Figure S3). Empirical cumulative distributions in Figure 3 show that intra-neighborhood differences were greater than inter-neighborhood differences for PNC and pPAH, while for CO, NO, NO_X, $PM_{2.5}$, and BC inter-neighborhood differences were greater than intra-neighborhood differences. In addition, Dorchester had particularly high levels of NO, NO_X, and CO and low levels of BC compared to the other neighborhoods.

Pollutant distance-decay gradients generally reached background within 200 m of I-93 when significant local sources were absent; therefore, 200 m was used as the cutoff for near-highway gradient calculations. Distance-decay gradients near I-93 were different for each near-highway neighborhood, with the steepest gradients occurring in Somerville and Dorchester (Figure 4). In Somerville and Dorchester PNC decreased by 34% and 30%, respectively, between 0-200 m from I-93, while the PNC distance-decay gradient in Chinatown was generally flat (2.2%; Table 4). Similarly, pPAH also decreased more in Dorchester (44%) and Somerville (39%) compared to Chinatown (21%). Somerville had the most pollutants with decreases of >20% within the first 200 m from I-93: PNC, BC, NO, NO_X, and pPAH. In Dorchester, only PNC and pPAH decreased by >20%. In Chinatown, CO, NO, and pPAH decreased by ~21% and all other pollutants decreased by <20%. The gradients from I-93 were stronger than those from I-90 in Chinatown: BC decreased by 8% and PNC decreased by 1%, while CO, NO, and NO_X increased by <8.3% over 200 m from I-90 and neither pPAH nor $PM_{2.5}$ had a significant trend over the same distance (Figure S4). In all three neighborhoods, PNC and pPAH had statistically significant distance-decay gradients within 200 m of I-93. In some cases, increasing pollutant concentrations with distance from I-93 were observed at distances greater than 200 m. In addition to those pollutants already mentioned, PNC and pPAH increased from 200 to 400 m west of I-93 in Dorchester as distance to a major urban roadway (Dorchester Avenue) decreased.

3.3. Temporal Differences

The effects of I-93 traffic volume were not the same for all pollutants in the three near-highway neighborhoods. PNC increased sharply in the three neighborhoods when traffic volumes were >~9,000 vehicles/hr (Figure S5), particularly during the morning rush hour when winds were lightest and (presumably) mixing height was lowest. Also, $PM_{2.5}$ generally increased with traffic volume in the three neighborhoods, and pPAH, CO, NO, and NO_x increased with traffic volume in Dorchester. In contrast, compared to differences among the neighborhoods, BC was largely unchanged with traffic volume, and pPAH, CO, NO, and NO_x concentrations were relatively unchanged as traffic increased in Somerville and Chinatown.

The effects of temperature on pollutant concentrations were similar for all neighborhoods. Temperature is an independent factor affecting air pollution formation and removal rates as well as a proxy for other seasonal factors (e.g., photochemical activity, mixing height). Temperature most strongly affected PNC and $PM_{2.5}$, which were highest in winter and summer, respectively (Figure S6). Other pollutants (CO, NO, NO_X, pPAH, BC) had small or non-monotonic changes with temperature. Likewise, the effects of wind speed were similar for all neighborhoods: concentrations generally decreased with increasing wind speed (Figures S3 and S7). Exceptions were $PM_{2.5}$ in Somerville and BC in Somerville and Dorchester, which increased in both magnitude and variability above ~6 m/s.

Effects of wind direction were different in each neighborhood. While the monitored near-highway areas generally had elevated pollutant concentrations when they were downwind of I-93, some areas also had high pollutant concentrations when the wind came from other directions (Figure S3). These differences were clearest for PNC, which had high concentrations for southeast winds in Somerville and Malden, northeast winds in Dorchester, and north and east winds in Chinatown. In Dorchester, concentrations of CO, NO, and NO_X were 2-4 times higher than in other neighborhoods and exceeded mean hourly concentrations in the study area for westerly winds (i.e., as high as 900 ppb CO, 60 ppb NO, and 100 ppb NO_X). In Chinatown, pollutant concentrations in the Washington Street canyon (which runs north-south) were highest for south winds from the direction of I-90 and lowest for north winds and west winds (Figure 5). Differences in concentrations for different wind directions were largest for $PM_{2.5}$ and smallest for NO and NO_X.

3.4. Inter-pollutant Correlations

Inter-pollutant correlations varied by neighborhood. Spearman correlations were higher among the gases (NO, NO_X, and CO) and lower among particulate pollutants (Figure 6). PNC was more highly correlated with the gases than with measures of particle mass. The correlations of NO with NO_X were consistently high in both near-highway and urban background areas in Somerville, Dorchester, and Chinatown/Malden. In general, correlations were lower in Dorchester than in other areas; the only correlation greater than

0.7 in the Dorchester near-highway area was for NO and NO_X (0.93). In contrast, the Somerville near-highway area had high correlations for many pollutant pairs, including NO_X and CO (0.76), NO_x and pPAH (0.83), and NO_x and PNC (0.80). As expected, $PM_{2.5}$ was not highly correlated with other pollutants in any of the study areas. Inter-pollutant correlations also varied by season and time of day: correlations were higher in cold months (November to March) than in warm months (April to October; Figure 7), and correlations were high during the morning rush hour (particularly when winds were light), low during the middle of the day, and high again during the afternoon rush hour (Figure 8).

A sensitivity analysis performed with the Chinatown data demonstrated that correlations were sensitive to aggregation times: correlations were usually higher for daily and hourly medians compared to 1 month and 1 min medians (Figure S8). Most inter-pollutant correlations were highest for measurements aggregated by day, although correlations of $PM_{2.5}$ with BC, PNC, and pPAH and of pPAH with BC were highest for monthly aggregation.

4. Discussion

We compared spatial and temporal TRAP trends in three near-highway and three urban background neighborhoods in a single urban corridor. Although each neighborhood had similar levels of local and diesel traffic and mobile source pollution and low levels of industrial or power plant emissions (Callahan, 2012; MassGIS, 2008a; U.S. Energy Information Administration, 2014), there were different spatial patterns in TRAP concentrations and inter-pollutant correlations. Pollutant levels generally increased with highway proximity, consistent with I-93 as a major TRAP source; however, distance-decay gradients varied by neighborhood in addition to season and time of day. In general, our results are consistent with studies that have reported pronounced distance-decay gradients of TRAP <200 m from highways and higher concentrations of TRAP near highways than in urban background neighborhoods (Durant et al., 2010; Hu et al., 2012; Kassomenos et al., 2014; Kittelson et al., 2004; Zhu et al., 2009). Previous studies have reported differences in air pollution in different neighborhoods (e.g., Bereznicki et al., 2012; Duvall et al., 2012; Fruin et al., 2014; Kassomenos et al., 2014); however, these differences were generally attributed to local sources such as industrial plants, power generation, or marine shipping terminals. Unlike Fruin et al (2014), we found only small differences in $PM_{2.5}$ ($\leq 3\ \mu g/m^3$) between neighborhoods, possibly because of the more substantial regional contribution to $PM_{2.5}$ in the Boston area relative to Southern California, as well as because the neighborhoods we monitored were closer together on average (1-30 km) than those in California (4-100 km).

Neighborhood geography including highway elevation and curvature, near-highway structures, and surface roads may help to explain observed differences in spatial variation of TRAP in the study neighborhoods. In Somerville, the influence of the elevated section of I-93 was larger than that of I-93 in Dorchester and I-90 in Chinatown, where the highway influence was likely reduced because the highways were below-grade (Steffens et al., 2014). Highway sections with large curvature (e.g., I-93 southeast of Somerville) potentially contributed to increased peak concentrations due to larger effective traffic volumes. On the other hand, noise barriers may have decreased peak concentrations east of I-93 in Somerville and west of I-93 in Dorchester (Finn et al., 2010; Hagler et al., 2012; Ning et al., 2010). In Chinatown, street-canyons between tall buildings may have altered wind flow so that meteorological data from Logan Airport was not representative of wind direction and speed within the study area. The general results in Chinatown, particularly for winds from the south, were consistent with entrainment of highway-generated TRAP in a street canyon (Kumar et al., 2008). In addition, examination of concentration patterns indicated contributions from major surface roads were often comparable in magnitude to contributions from highways. This effect was largest in Dorchester and Chinatown, where at-grade traffic on major roads may have had more influence than direct emissions from I-93 and I-90. For example, Kneeland St and E Berkeley St contribute to air pollution in Chinatown because they provide access to highway ramps and have high-volume intersections (Massachusetts Bay Transportation Authority, 2005).

Although monitoring in all three near-highway areas was conducted over a similar range of meteorological and traffic conditions, some differences in pollutant concentrations and distance-decay gradients in the neighborhoods could not be explained by highway traffic data or data from the regional meteorological station. Traffic on local roadways may explain some of those differences, particularly in Dorchester, where CO and NO_X concentrations were consistently higher than in other neighborhoods. Our study was not designed to formally capture sources other than highway vehicles, but evidence regarding different wind direction effects in the different neighborhoods can be used to generate hypotheses regarding important non-highway sources. For example, high PNC concentrations occurred for wind directions (including southeast in Somerville and Malden, northeast in Dorchester, and east in Chinatown) when the neighborhoods were downwind of downtown Boston and Logan Airport, which contain several potential emissions sources including surface transportation (roads and rail) and aircraft.

Correlations were generally strongest during times when there were high levels of fresh emissions (e.g., during rush hour) and during colder months (October-May). Higher correlations during cold months are consistent with the literature and may also be related to more favorable formation conditions for certain pollutants (e.g., ultrafine particles), greater atmospheric stability and lower photochemical activity during cooler times of the year (Kittelson et al., 2004; Kumar et al., 2014; Venkatram et al., 2013). These differences are unlikely to be related to traffic volume, which differed by ≤3% between warm and cold seasons. Correlations are useful to test our understanding of the sources and mixing; correlations among pollutants emitted from the same source should be high, while lower correlations may indicate another source or the presence of aged TRAP. Higher inter-neighborhood variation of $PM_{2.5}$ than intra-neighborhood variation (one-way ANOVA) and generally low correlations of $PM_{2.5}$ with the other pollutants suggest that $PM_{2.5}$ was more regional while the other pollutants had local sources, consistent with expectations.

There were limitations in our data collection and analysis methods. First, the study was conducted with hourly meteorological data from a single weather station that was ~4-12 km from the study areas. Local wind effects such as wind tunnels between rows of buildings were not captured by the station at Logan Airport. Second, traffic parameters were based on highway counts. TRAP sources that are not captured in the available datasets (e.g., diurnal variation in congestion and diesel traffic on local roads) may also explain some of the observed inter-neighborhood differences. Third, distance-decay gradients measured by the mobile laboratory for pollutants with longer measurement times (BC, NO, NO_X, CO) may be underestimated; therefore, comparison of distance-decay gradients would possibly have yielded different results had all the monitors recorded measurements at the same frequency. These limitations do not significantly affect our main result that there are both intra- and inter-neighborhood differences in TRAP along I-93 in the Boston area.

The finding that the near-highway neighborhoods are different in terms of TRAP has two main implications for health studies in small areas. First, distance-decay gradients measured in one near-highway neighborhood are not necessarily transferable to other neighborhoods, even along the same highway in a metropolitan area. In health studies involving comparison of different neighborhoods, monitoring in multiple locations at different times may be required to characterize gradients particularly where there are (1) pronounced changes in highway grade or curvature, or (2) changes in near-highway structures, vegetation, and building height or density. Second, consideration of multiple pollutants may be necessary given that the causal pollutant(s) within TRAP have not yet been delineated. Using a single surrogate pollutant may lead to differential error across neighborhoods, as the surrogate will represent different combinations of pollutants across locations. The variable patterns within a day suggest that these differences may be particularly important in short-term studies, which will need to account for multi-pollutant correlations that change in both space and time.

5. Conclusions

Our results indicate that generalizability of near-road gradients and near-highway/urban background contrasts is limited for near-highway neighborhoods in a metropolitan area with substantial mobile source emissions. Near-highway distance-decay gradients of TRAP concentrations and inter- pollutant correlations were not the same in different neighborhoods along a single highway through an urban area. Differences were not completely explained by temporal variation, including traffic patterns or seasonal or diurnal effects. These differences may be related to local infrastructure, traffic congestion, and non-traffic sources of air pollution. Our results suggest that caution should be used when assuming similarity of near-highway areas for epidemiological studies because even measuring several gradients at different locations along a highway may underestimate the true variability in distance-decay gradients in urban areas. These findings may be particularly relevant for metropolitan areas like Boston where, due to roadside structures, highway geometry, and local wind and traffic patterns, near-highway neighborhoods will exhibit dissimilar air pollution impacts from mobile sources.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We compared traffic-related air pollution in 3 Boston-area neighborhoods near I-93.
- Pollutant distance-decay gradients were different in each neighborhood.
- Pollutant correlations varied by neighborhood, season, and time of day.

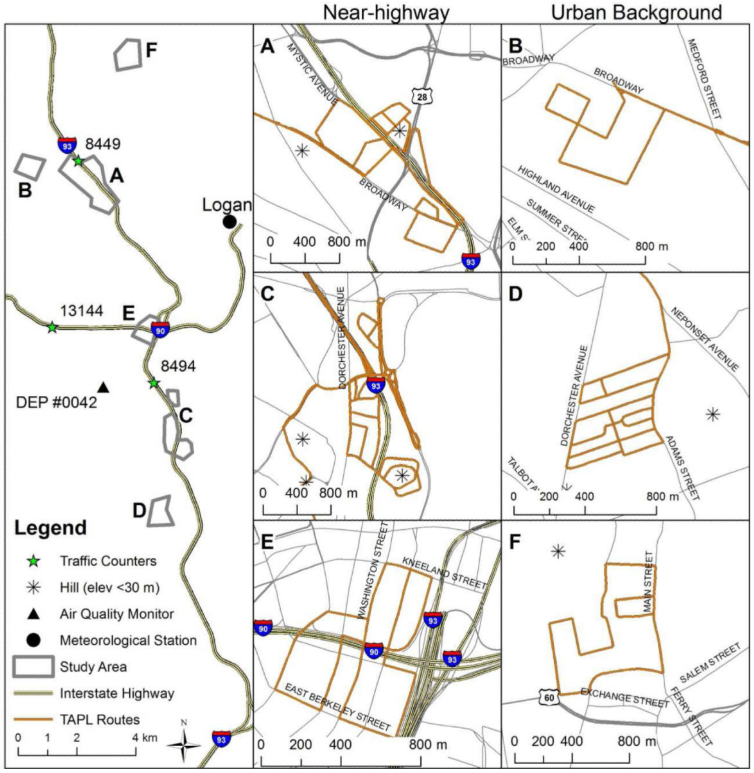


FIGURE 1.

Mobile Monitoring Areas And Driving Routes. Somerville Near-Highway (A) And Urban Background (B) Were Monitored FRom September 2009 Through August 2010; Dorchester Near-Highway (C) And Urban Background (D) Were Monitored FRom September 2010 Through August 2011; Chinatown (Near-Highway; E) Malden (Urban Backgroung; F) Were Monitored From August 2011 Through July 2012. “Dep#0042” Is A Boston Epa Speciation Trends Network Site (Id: 25-025-0042). Road Layers FRom Massgis (2008A).

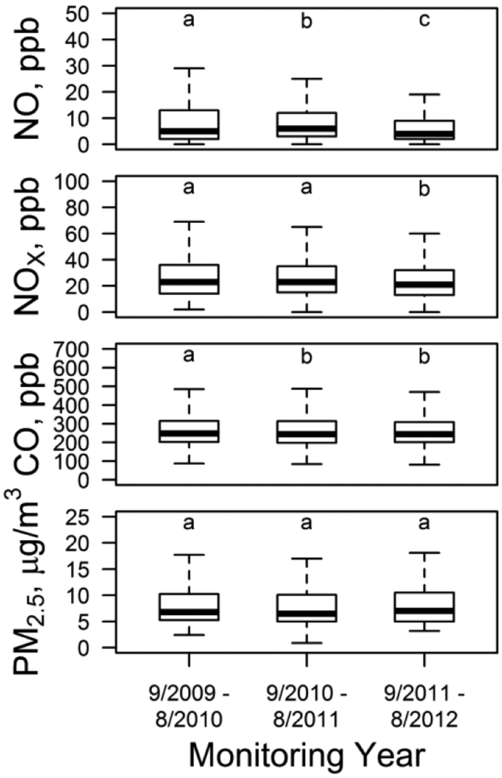


FIGURE 2.

Tukey Boxplots Comparing No, No$_x$, Co, And PM$_{2.5}$ Measure At Stn Site 25-025-0042 In Boston (Figure 1) For Each Full Mobile Monitoring Year. Whisker Lengths Are The Smaller Value Of 1.5*Iqr And The Distance To The Maximum Or Minimum (Outliers Not Shown). Common Letters Above The Boxes for Each Pollutant Identify Groups That Are Not Significantly Different At the 95% Condidence Interval Using Kruskal-Wallace Mulpiple Comparisons Test. Data is From *Ma Dep (2012)*

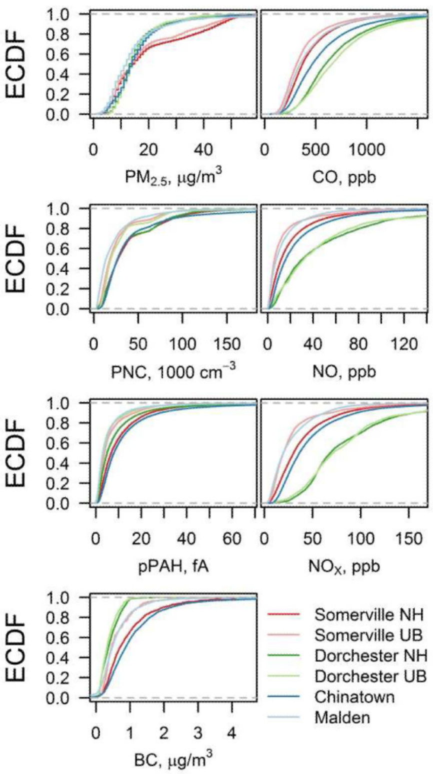


FIGURE 3.

Empirical Cumullative Distribution Functions For Particles (Left Side: $Pm_{2.5}$, Pnc, Ppah, BC) And Gases (Right Side: Co, No, No_X) For Someriville Near-Highway (Nh) And Urbam Backgrougn (Ub), Dorchester Near-Highway And Urban Background, Chinatown Near-Highway, And Malden Urban Background Study Areas. The X-Axis Maxima Were Set At The 99Th Percentile Of Near-Highway Measurements In Somerville.

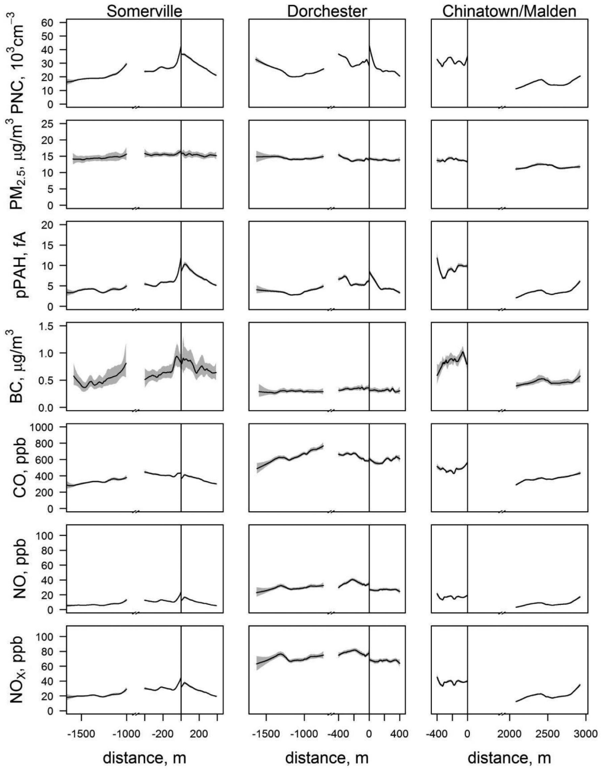


FIGURE 4.

Loess Smooths (Black Lines) With 95% Confidence Intervals (Grey Shading) For Pnc, Pm$_{2.5}$, Ppah, Bc, Co, No, And Nox, As A Function Of Distance From The Nearest Edge Of I-93 (Vertical Black Lines) For Somerville (Left), Dorchester (Center), And Chinatown/ Malden (Right). Each Plot Has A Break Between The Near-Highway And Urban Background. The Only Urban Background Area East Of I-93 Is Malden. Distances East Of I-93 Are Positive And Distances West Of I-93 Are Negative.

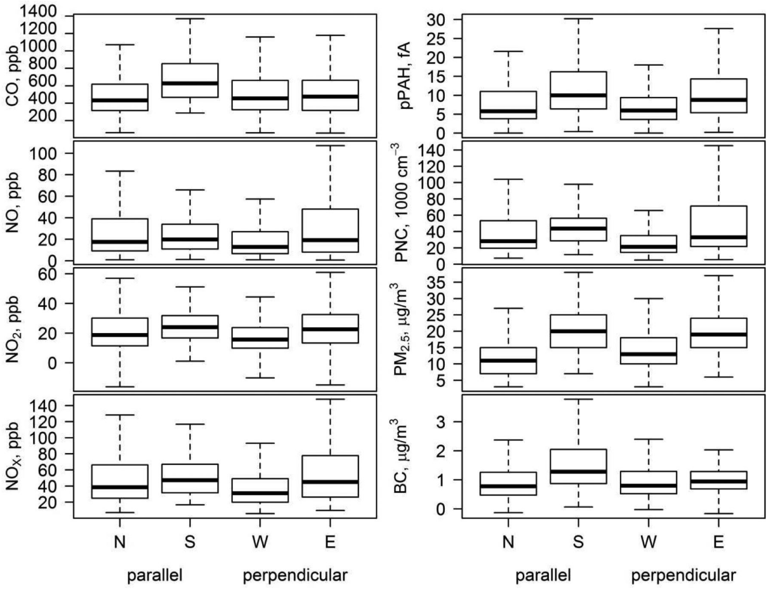
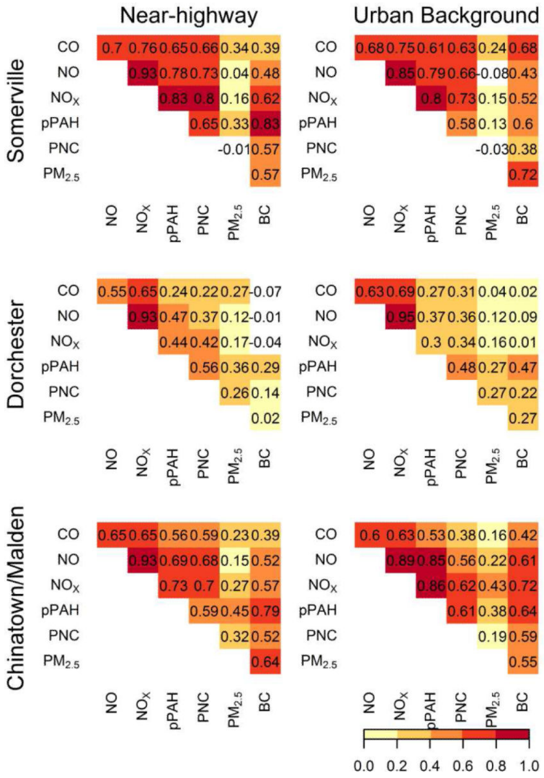


FIGURE 5.

Tukey Boxplots Of Co, No, No$_2$ No$_x$, Ppah, Pnac, Pn$_{2.5}$, Bc Concentrations On Washington Street (Street Canyon In Chinatown) As A Function Of Wing Direction Relative To The Street Orienatation. Whisker Lengths Are The Smaller Value Of 1.5*Iqr And The Distance To The Maximum Or Minimum (Outliers Not Shown).



Somerville

	Near-highway							Urban Background					
	NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC		NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC
CO	0.7	0.76	0.65	0.66	0.34	0.39	CO	0.68	0.75	0.61	0.63	0.24	0.68
NO		0.93	0.78	0.73	0.04	0.48	NO		0.85	0.79	0.66	-0.08	0.43
NO$_X$			0.83	0.8	0.16	0.62	NO$_X$			0.8	0.73	0.15	0.52
pPAH				0.65	0.33	0.83	pPAH				0.58	0.13	0.6
PNC					-0.01	0.57	PNC					-0.03	0.38
PM$_{2.5}$						0.57	PM$_{2.5}$						0.72

Dorchester

	NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC		NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC
CO	0.55	0.65	0.24	0.22	0.27	-0.07	CO	0.63	0.69	0.27	0.31	0.04	0.02
NO		0.93	0.47	0.37	0.12	-0.01	NO		0.95	0.37	0.36	0.12	0.09
NO$_X$			0.44	0.42	0.17	-0.04	NO$_X$			0.3	0.34	0.16	0.01
pPAH				0.56	0.36	0.29	pPAH				0.48	0.27	0.47
PNC					0.26	0.14	PNC					0.27	0.22
PM$_{2.5}$						0.02	PM$_{2.5}$						0.27

Chinatown/Malden

	NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC		NO	NO$_X$	pPAH	PNC	PM$_{2.5}$	BC
CO	0.65	0.65	0.56	0.59	0.23	0.39	CO	0.6	0.63	0.53	0.38	0.16	0.42
NO		0.93	0.69	0.68	0.15	0.52	NO		0.89	0.85	0.56	0.22	0.61
NO$_X$			0.73	0.7	0.27	0.57	NO$_X$			0.86	0.62	0.43	0.72
pPAH				0.59	0.45	0.79	pPAH				0.61	0.38	0.64
PNC					0.32	0.52	PNC					0.19	0.59
PM$_{2.5}$						0.64	PM$_{2.5}$						0.55

FIGURE 6.

Spearman Correlations of Pollutions (Hourly Median) By Study Area.

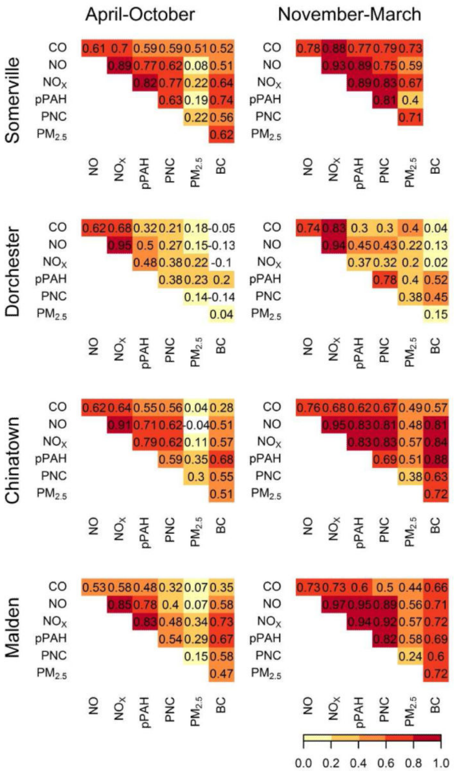
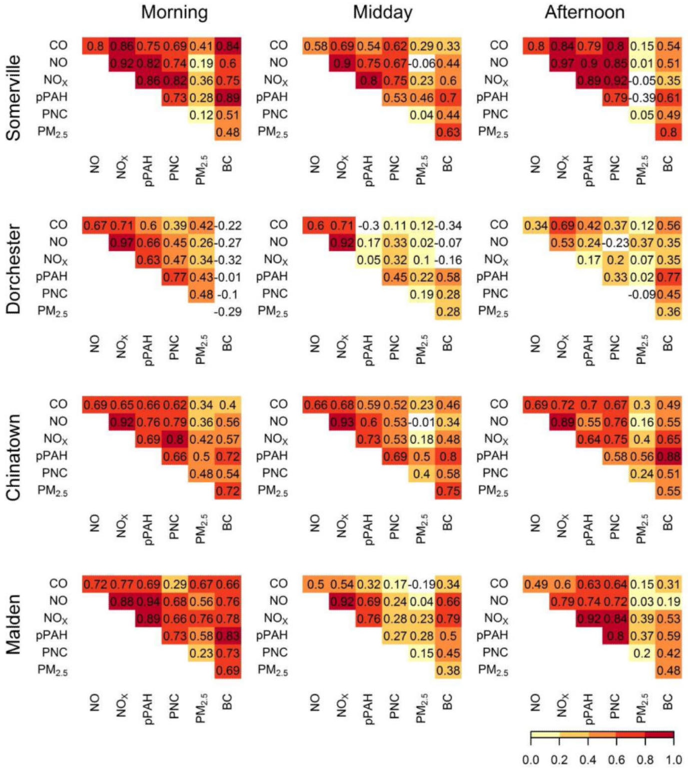


FIGURE 7.

Spearman Correlations For Warm (April To October) And Cole (November To March) Months For Someville, Dorchester, Chinatown, And Malden. The Bc Monitor Was Not Running During The Cold Months In Somerville.



	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.8	0.86	0.75	0.69	0.41	0.84
NO		0.92	0.82	0.74	0.19	0.6
NO_X			0.86	0.82	0.36	0.75
pPAH				0.73	0.28	0.89
PNC					0.12	0.51
$PM_{2.5}$						0.48

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.58	0.69	0.54	0.62	0.29	0.33
NO		0.9	0.75	0.67	-0.06	0.44
NO_X			0.8	0.75	0.23	0.6
pPAH				0.53	0.46	0.7
PNC					0.04	0.44
$PM_{2.5}$						0.63

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.8	0.84	0.79	0.8	0.15	0.54
NO		0.97	0.9	0.85	0.01	0.51
NO_X			0.89	0.92	-0.05	0.35
pPAH				0.79	-0.39	0.61
PNC					0.05	0.49
$PM_{2.5}$						0.8

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.67	0.71	0.6	0.39	0.42	-0.22
NO		0.97	0.66	0.45	0.26	-0.27
NO_X			0.63	0.47	0.34	-0.32
pPAH				0.77	0.43	-0.01
PNC					0.48	-0.1
$PM_{2.5}$						-0.29

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.6	0.71	-0.3	0.11	0.12	-0.34
NO		0.92	0.17	0.33	0.02	-0.07
NO_X			0.05	0.32	0.1	-0.16
pPAH				0.45	0.22	0.58
PNC					0.19	0.28
$PM_{2.5}$						0.28

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.34	0.69	0.42	0.37	0.12	0.56
NO		0.53	0.24	-0.23	0.37	0.35
NO_X			0.17	0.2	0.07	0.35
pPAH				0.33	0.02	0.77
PNC					-0.09	0.45
$PM_{2.5}$						0.36

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.69	0.65	0.66	0.62	0.34	0.4
NO		0.92	0.76	0.79	0.36	0.56
NO_X			0.69	0.8	0.42	0.57
pPAH				0.66	0.5	0.72
PNC					0.48	0.54
$PM_{2.5}$						0.72

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.66	0.68	0.59	0.52	0.23	0.46
NO		0.93	0.6	0.53	-0.01	0.34
NO_X			0.73	0.53	0.18	0.48
pPAH				0.69	0.5	0.8
PNC					0.4	0.58
$PM_{2.5}$						0.75

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.69	0.72	0.7	0.67	0.3	0.49
NO		0.89	0.55	0.76	0.16	0.55
NO_X			0.64	0.75	0.4	0.65
pPAH				0.58	0.56	0.88
PNC					0.24	0.51
$PM_{2.5}$						0.55

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.72	0.77	0.69	0.29	0.67	0.66
NO		0.88	0.94	0.68	0.56	0.76
NO_X			0.89	0.66	0.76	0.78
pPAH				0.73	0.58	0.83
PNC					0.23	0.73
$PM_{2.5}$						0.69

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.5	0.54	0.32	0.17	-0.19	0.34
NO		0.92	0.69	0.24	0.04	0.66
NO_X			0.76	0.28	0.23	0.79
pPAH				0.27	0.28	0.5
PNC					0.15	0.45
$PM_{2.5}$						0.38

	NO	NO_X	pPAH	PNC	$PM_{2.5}$	BC
CO	0.49	0.6	0.63	0.64	0.15	0.31
NO		0.79	0.74	0.72	0.03	0.19
NO_X			0.92	0.84	0.39	0.53
pPAH				0.8	0.37	0.59
PNC					0.2	0.42
$PM_{2.5}$						0.48

FIGURE 8.

Spearman Correlations In Each Study Area By Time Of Day. Morning = 04:30-10:00, Midday = 10:00-14:00, And Afternoon = 14:00-22:00.

Table 1

Study areas.

Area	Area (km^2)	Monitoring period	Interstate Highways	Other major roads[a]	Local diesel sources[b]	Buildings and roadside structures	Topographic features[c]
Somerville	2.3	Sept. 2009 to Aug. 2010	I-93 (elevated in parts as much as 6 m, curves SE of study area)[d]	MA-28 (50); Broadway (14)	trucks <500 vpd; 200 trains/day ~100 m NE of background area	residences (~10-m high); 400-m-long noise barrier east of I-93 (3-m high)	17 m hill east of I-93; 41 m hill between near-highway and urban background areas
Dorchester	1.5	Sept. 2010 to July 2011	I-93 (3-6 m below grade)	Dorchester Ave (20), Old Colony Rd (36), Columbia Rd (20), and Adams St (9)	<500 vpd; 110 trains/day adjacent to west side of I-93	residences (~10 m high); noise barrier along west side of I-93 (5-m-high)	34 m hill east of I-93; east to west elevation increase from 0 m to 30 m
Chinatown	0.5	Aug. 2011 to July 2012	I-93 (at-grade),[e] I-90 (below grade)	All other roads on the TAPL route (2 or 9)	<500 – 1000 vpd; buses plus 347 trains/day[f]	residences and commercial buildings (up to 100-m tall); street canyons[g]	2-8 m above sea level
Malden	0.7	Aug. 2011 to July 2012	None	MA-60 (20)	<500 vpd; 58 trains/day	Residences (mostly ~10 m high, some 6-8 story apartments)	7–18 m above sea level

[a] Other highways and major roads in the study areas with their average daily traffic 4 in thousands of vehicles per day from MassGIS (2008b).

[b] Diesel truck volumes from Callahan (2012) and Central Transportation Planning Staff (2012). Estimated diesel train volumes are the total of commuter (http://www.mbta.com/uploadedfiles/documents/2014%20BLUEBOOK%2014th%20Edition.pdf) and AMTRAK (http://www.amtrak.com/train-schedules-timetables) trains near and in the study areas.

[c] Elevation data was obtained from the Massachusetts Digital Elevation Model (MassGIS, 2005). Building heights and number of floors from http://skyscraperpage.com/cities/maps/?cityID=145.

[d] The I-93 corridor in Somerville also includes Mystic Avenue, which contributes 30,000 vehicles per day (vpd) at grade (Central Transportation Planning Staff, 2012).

[e] The I-93 central artery tunnel comes above ground just northeast of the study area, and I-93 is elevated along the study area.

[f] A train and bus depot (South Station) is located east of I-93 near the study area and commuter rail (diesel) train tracks run along I-90 southeast of the study area.

[g] The tallest two buildings in the Chinatown study area are 92 m (25 stories) and 79 m (23 stories).

Table 2

Summary of monitoring years and site conditions during monitoring.

		Somerville	Dorchester	Chinatown	Malden
Year		9/2009–8/2010	9/2010–8/2011	8/2011–7/2012	8/2011–7/2012
# of monitoring days		44	35	47	36
# of monitoring hours		281	173	141	85
# April – October hours [a]		152	90	83	57
# November – March hours [a]		129	83	58	28
Parameter					
Wind speed, m/s[b]		2.6 (1.6)	3.0 (2.1)	2.9 (1.6)	2.4 (1.3)
Temperature, °C[b]		11.05 (16.6)	9.15 (11.1)	14.4 (10.6)	14.8 (13.8)
Day of week, percent of full dataset	Sun	6%	10%	10%	2%
	Mon	8%	11%	4%	8%
	Tues	18%	10%	19%	11%
	Wed	27%	24%	20%	33%
	Thurs	24%	15%	13%	32%
	Fri	4%	17%	21%	9%
	Sat	14%	12%	14%	5%
I-93 Traffic volume, vph[b]		8500 (1800)	9600 (1000)	9600 (1400)	N/A
I-93 Traffic speed, kph[b]		83 (29)	86 (15)	86 (16)	N/A
I-90 Traffic volume, vph[b]		N/A	N/A	7086(3526)	N/A
I-90 Traffic speed, kph[b]		N/A	N/A	90 (5)	N/A

[a] Monitoring hours are split into warm (April to October) and cold (November to March) months.

[b] Data are summarized by mean with interquartile range in parentheses.

Table 3

Summary of pollutant measurements for each study area.

	Somerville[a]			Dorchester[a]			Chinatown/Malden[a]		
	NH	**UB**	**P[b]**	**NH**	**UB**	**P[b]**	**NH**	**UB**	**P[b]**
CO, ppb	390 (310)	310 (230)	<0.001	600 (420)	660 (450)	1[c]	460 (380)	344 (280)	<0.001
NO, ppb	15 (26)	6 (11)	<0.001	31 (50)	32 (46)	0.50	16 (24)	8 (15)	<0.001
NOx, ppb	33 (39)	20 (20)	<0.001	67 (56)	71 (54)	0.55	36 (35)	20 (27)	<0.001
pPAH, fA	8 (12)	4 (6)	<0.001	5 (8)	3 (5)	<0.001	8 (11)	3 (5)	<0.001
PNC, 1000 cm^{-3}	30 (49)	18 (19)	<0.001	27 (33)	19 (20)	<0.001	26 (26)	14 (20)	<0.001
$PM_{2.5}$, µg m^{-3}	15 (23)	14 (17)	<0.001	13 (8)	14 (7)	1[c]	14 (9)	12 (9)	<0.001
BC, µg m^{-3}	0.8 (0.9)	0.5 (0.5)	<0.001	0.4 (0.4)	0.3 (0.3)	<0.001	0.8 (0.9)	0.5 (0.5)	<0.001

[a] Median pollutant levels with IQR in parentheses for NH = near-highway (<400m from edge of I-93) and UB = urban background (>1000 m from edge of I-93) areas.

[b] P-values are based on Wilcoxon rank sum test of the null hypothesis that near-highway concentrations are ≤ urban background concentrations.

[c] Urban background concentrations were statistically significantly greater than near-highway concentrations.

Table 4

Distance-decay gradients of pollutant concentration within 200 m of highway edge.

	Somerville: I-93			Dorchester: I-93			Chinatown: I-93			Chinatown: I-90		
	Estimate[a]	**Decrease, %**		**Estimate**[a]	**Decrease, %**	**p**[b]	**Estimate**[a]	**Decrease, %**	**p**[b]	**Estimate**[a]	**Decrease, %**	**p**[b]
PNC	−0.204	**33.5**	<0.001	−0.176	**29.7**	<0.001	−0.011	2.2	0.003	−0.005	1	<0.001
BC	−0.17	**29**	0.0007	−0.03	6	0.4	−0.02	4	0.7	−0.04	8	0.001
CO	−0.007	1	0.3	0.009	−2	0.3	−0.121	**21.5**	<0.001	0.040	−8.3	<0.001
NO	−0.21	**34**	<0.001	−0.01	2	0.6	−0.12	**21**	<0.001	0.021	−4.3	<0.001
NO_x	−0.130	**23**	<0.001	−0.01	2	0.4	−0.07	10	<0.001	0.012	−2.4	<0.001
pPAH	−0.25	**39**	<0.001	−0.29	**44**	<0.001	−0.12	**21**	<0.001	0.002	−0.4	0.7
$PM_{2.5}$	−0.02	4	0.09	−0.016	3.1	0.08	0.029	−6.0	<0.001	−0.001	0.2	0.8

[a] Estimate is the % change in the logarithm of the pollutant concentrations per 100 m away from the edge of the highway. It was obtained by multiplying the coefficient of the simple log-linear regression of concentration as a function of distance times 100.

[b] The percent decrease over 200 m is calculated as 100*[exp(Estimate/100*200)-1] (Wooldridge, 2012). Decreases ≥ 20% are bold.

[c] P-value for the Estimate coefficient.