Environ Monit Assess (2014) 186:4605–4618
DOI 10.1007/s10661-014-3723-8

Black carbon concentrations in a goods-movement neighborhood of Philadelphia, PA

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Received: 7 October 2013 / Accepted: 6 March 2014 / Published online: 26 March 2014

Abstract Communities along the Delaware River in Philadelphia, USA such as Port Richmond, are subject to traffic associated with goods movement to and from port facilities and local industry. Air pollution associated with this traffic poses an environmental health concern in this and other urban areas. Our study measures black carbon (BC) in Port Richmond and examines its relationship to expected sources such as truck traffic. We used a participatory sampling method to conduct 1-min measurements over 8-hour periods at 14 homes, a school and park, during a 4-week period in June 2012. Measurements over 9 sampling days had a 30-min average BC concentration of 1.2 μg m^{-3}, and a maximum of 12 μg m^{-3}. Statistical analyses showed some effect of traffic, but greater association between BC concentrations and weather and time of day. BC concentrations varied more by location than by day, and distance to traffic arterials and interstate freeway was a predictor of this variance. While our dataset is limited by number and variety of observations, major findings indicate that BC concentration varies more by location than by day, there is a decrease in median BC concentration with increased distance from an interstate highway, and an expected effect of diesel traffic on average daily BC concentrations. Our findings are an important step towards understanding patterns and determinants of BC concentration in communities colocated with major ports. Our study also demonstrates that participatory methods in air pollution monitoring can help increase awareness of local air pollution levels.

Keywords Black carbon · Air pollution · Participatory methods · Goods movement · Port

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Introduction

Land use and transportation policies, and built environments can significantly affect public health and the environment (Frumkin 2002; Seto et al. 2007). States and local governments especially in areas of high population growth are increasingly enacting policies that promote compact, infill, and transit-oriented development. These policies aim to increase the efficiency of infrastructure and resource use, reduce greenhouse gas emissions, promote walkability and public health, and conserve ecologically sensitive regions within and surrounding urban areas (United States Environmental

Protection Agency and Smart Growth Network 2006; Freilich et al. 2010). While there are documented public health benefits of compact mixed-used development, other studies suggest that increased use and activities within industrial and high-traffic areas also means increased human exposure to air pollution (Marshall et al. 2009; Schweitzer and Zhou 2010; Giles et al. 2011).

The near-roadway environment is a prominent concern due to documented elevated concentrations of ultrafine particles and gases from combustion (Zhu et al. 2002a, b) and metals (Wilkinson et al. 2013), and exposure to many of these pollutants has been associated with increased incidence of asthma and respiratory infections (Brauer et al. 2002, 2007; Gordian et al. 2005; Kim et al. 2008), low birth weight and preterm birth (Brauer et al. 2007; Wu et al. 2009) and cardiopulmonary mortality (Brunekreef et al. 2009; Hoek et al. 2002). There is increasing concern among scientists, policy makers, and the public about diesel exhaust in particular. Emerging research shows a noticeable association between health outcomes and proximity to roadways with heavy truck traffic, thereby particle and gas pollution from diesel combustion (Brunekreef et al. 1997; Janssen et al. 2003). In 2012, diesel exhaust was categorized as a *Class 1 Carcinogen* by the International Agency for Research on Cancer of the World Health Organization (World Health Organization International Agency for Research on Cancer 2012).

Philadelphia residents (23 % of children; 17 % of adults) suffer from high rates of asthma in comparison to national averages (9.4 % of children; 7.7 % of adults) (City of Philadelphia Department of Public Health—Air Management Services 2010). At present, it is not possible to assess whether an elevated asthma level is related to air pollution. Air pollution (not including black carbon) in Philadelphia is currently monitored at 10 sites by Air Management Services, a division of the Philadelphia Department of Public Health. While this is an extensive network, this data cannot detect variation in pollution levels (especially black carbon) at the neighborhood, street, or individual level even though these differences could have a meaningful connection to health (Zhu et al. 2002a, 2009). Neighborhood-scale monitoring is an effective way to determine the spatial patterns of pollutant concentrations throughout a community and identify local pollution sources.

Earlier studies measuring components of diesel exhaust particles (DEP) have shown local-level variation in concentrations are associated with the volume of truck traffic (Lena et al. 2002; Kinney et al. 2000) using black carbon (BC) as a measure of DEP. BC is a component of PM, and is a product of incomplete combustion (fuel combustion or biomass burning). In major metropolitan areas, vehicle exhaust, and in particular diesel exhaust, is the dominant source of BC (U.S. Environmental Protection Agency 2010). For this reason, the concentration of BC is a strong indicator of traffic's overall effect on urban air quality (Reche et al. 2011). BC also impacts climate through several pathways exerting a warming effect on regional and global climate (Ramanathan and Carmichael 2008; Intergovernmental Panel on Climate Change 2007) and has been characterized as second to only CO_2 in terms of positive net climate forcing effect (Bond et al. 2013). Our study measures BC concentrations at scattered locations in Port Richmond, a neighborhood in NE Philadelphia, and explores their relationship to expected sources such as truck traffic. We use a participatory sampling method with community members to conduct 8-hour measurements at multiple locations over a 4-week measurement period in May–June 2012.

Location

The city of Philadelphia (pop. 1,547,607 in 2012) is located at the confluence of the Schuylkill and Delaware Rivers (Fig. 1). While the Schuylkill River (which bisects the west side of the city) has long been a source of drinking water to the region, the Delaware River (which bounds the city to the east and south) has long been a means of goods movement to and from Philadelphia and its neighbors to the west. The Philadelphia Regional Port Authority currently manages seven facilities along the Delaware River. The City is preparing to increase the volume of goods movement through its port facilities; in 2011, a dredging project to deepen a 103-mile stretch of the river channel began. In addition, the Delaware River corridor has been a home to heavy industry starting in the nineteenth century.

Diesel truck traffic associated with port and industry activities is a prominent issue for Delaware River communities such as Port Richmond (see Fig. 1). Port Richmond has been home to generations of industrial activity (Sicotte 2010), including smelters and chemical plants, sewage treatment plants, and chromium plating facilities. In addition, Port Richmond is home to the Tioga Marine Terminal, where ocean-going vessels, cargo-

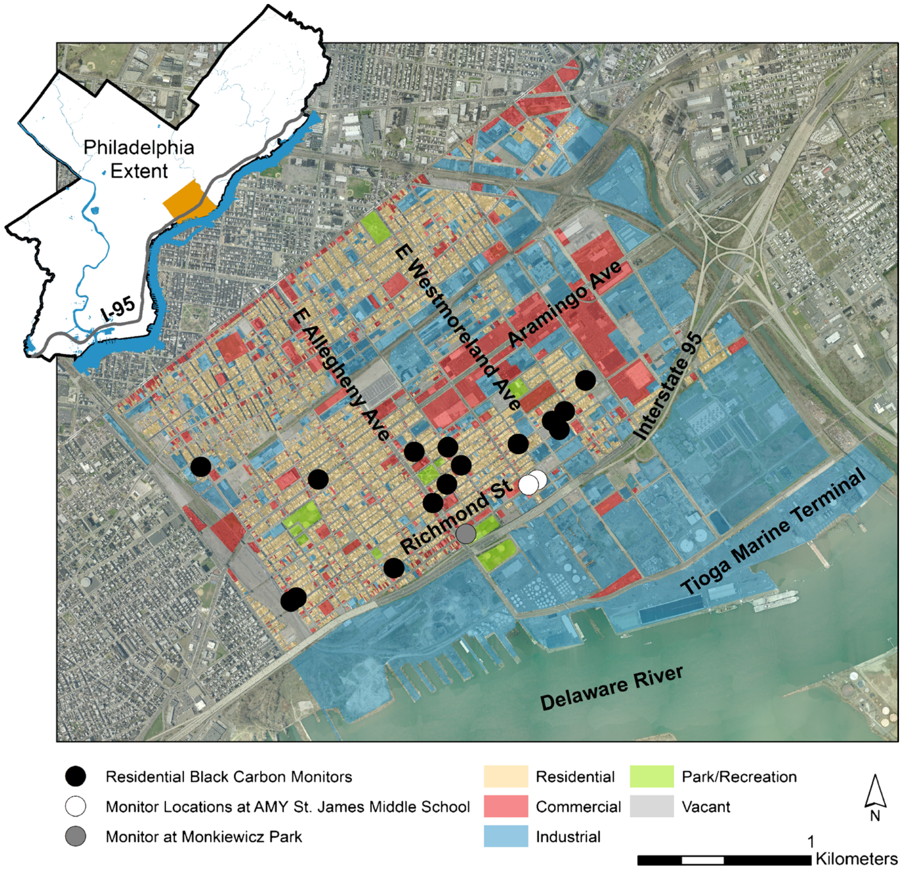

Fig. 1 Land use and black carbon monitor locations

handling equipment, and truck traffic combine to create a major source of air pollution. Interstate-95, which now runs parallel to the Delaware River and eastern edge of the city (Fig. 1), was built through the neighborhood in 1960s and 1970s, increasing the volume of traffic and by extension vehicular exhaust through the neighborhood. The highway now effectively separates residential areas from industry along the Delaware River shoreline.

According to the 2010 U.S. Census, Port Richmond has a total population of 38,218. Eighteen percent are African American, 2 % are Asian, 63 % Non-Hispanic White, and 15 % belongs to "other" races. Foreign-born residents represent 11 % of the population. The neighborhood has a strong Polish community and history. Port Richmond is an economically diverse neighborhood; it is home to working professionals and working class. In addition, 35 % of residents earn salaries at or below the federal poverty level, and over 10 % of residents over the age of 16 are unemployed (U.S. Bureau of the Census 2010).

Asthma rates in this neighborhood (26 % of children; 23 % of adults) are higher than city- and national averages. Based on our initial outreach in the neighborhood, many residents are very concerned about truck traffic as sources of environmental health and safety hazards, and overall detractors from quality of life. They associate pollution from trucks and industry with health problems in the neighborhood such as asthma.

Heavy-duty diesel traffic is concentrated on Richmond Street and E Allegheny Avenue, although these vehicles also utilize side streets (see Fig. 1). Richmond St parallels I-95 approximately 100 m to the northwest and is bordered by commercial, park, and manufacturing uses, as well as sensitive land uses including residences, daycare facilities, and schools (e.g., AMY James Martin Middle School). According to community participants, Richmond St had been a quiet commercial district prior to the mid 1970s. After the completion of the Port Richmond stretch of I-95 in the late 1960s and the addition of the E Allegheny Ave exit half a decade later, the community experienced a significant increase in automobile traffic on neighborhood streets. Residents resisted the proposed addition of the Allegheny exit along the interstate, fearing an increase in traffic through the neighborhood, but were unable to prevent its development. E Allegheny Ave is a major four-lane east-west thoroughfare (which we found to carry up to 1,000 vehicles per hour). It is lined by a mixture of uses, including commercial, residential, and institutional.

In 2011, a partnership between community members in Port Richmond, Clean Air Council, and scholars at the University of Pennsylvania and Drexel University formed to address concerns regarding air pollution. We aimed to collect and analyze real-time measurements of both traffic and pollutant indicators of diesel truck exhaust. The goal is that analyses will assist in promoting policies or other solutions to reduce exposure to diesel-related air pollution.

Material and methods

Recruitment and community involvement

This study is one product of a developing partnership between active citizens in Port Richmond, Clean Air Council, and scholars at the University of Pennsylvania and Drexel University. While Port Richmond residents have long been concerned about local air pollution and truck idling, nonprofit and academic partners had not assisted them with research needs on this issue prior to 2011. At that time, Clean Air Council and its academic partners learned of residents' concerns and began developing relationships with the community, including organizations and institutions acting in Port Richmond. We learned about specific environmental health and safety concerns and the location of suspected air pollution "hotspots" via this outreach and semi-structured interviews. Other past studies have included personal exposure monitoring for $PM_{2.5}$, and a Photovoice exercise. Resident's complaints of "soot" in and around their homes were one motivation to measure black carbon in the current study. Results of this study are detailed in a separate article (Kondo et al. 2014).

Outreach and recruitment protocol for this and past research was reviewed and approved by the University of Pennsylvania's Institutional Review Board. This study used purposive sampling, a nonrandom method, to recruit participants. Multiple participants from past studies asked to be involved in the current study. In addition, we recruited participants via announcements at community meetings and in the local newspaper. We excluded one potential location from the study due to its proximity to a major road construction project. The research design incorporated participants' input on local black carbon sources and traffic hotspots. Participants were compensated monetarily for each monitoring day in which they participated.

Black carbon measurements

To characterize BC concentrations in Port Richmond, we collected 8-h measurements with 4 micro-Aethalometers ("micro-Aeth"; AE-51, Magee Scientific, Berkeley CA) at 17 outdoor fixed locations (3–4 locations at one time; with repeat measurements at 6 locations) between May 23 and June 29, 2012. Due to malfunction, we discontinued use of the fourth micro-Aeth after the second sampling day. Nine sampling days consisted of eight weekdays and one weekend day. We conducted sampling at 6 of the sample locations more than once, and made a total of 26 unique measurements of approximately 8-h duration (between 9 am and 5 pm).

The micro-Aeths were powered by rechargeable battery, with a measurement time base of 1 min, and airflow rate of 100 mL/min. Micro-Aeths determine BC concentrations by monitoring the change in light attenuation as particles are deposited on a filter. Attenuation (or absorption) of light increases as more BC mass is deposited on the filter. Previous studies have found that particle accumulation on filters enhances light absorption (Jimenez et al. 2007), and therefore we replaced filters daily. Changes in attenuation are converted into BC concentrations and recorded in nanograms (ng) of particles per cubic meter (m^3) of air. We performed binomial smoothing of micro-Aeth data output to reduce erratic oscillation.

To test the accuracy and inter-comparability of the micro-Aeths, we performed three duplicate checks: before, during, and after the monitoring period. Prior to monitoring, for baseline testing and quality control, we ran all micro-Aeths inside a sealed plastic container for 8 h and then outside the container for 8 h. Baseline testing inside the sealed container occurred from 9 pm to 6 am, followed by 8 h outside of the container. We performed a side-by-side duplicate intercomparison to characterize the reproducibility of the BC measurements by the four micro-Aeths.

We placed micro-Aeths in outdoor locations at participating locations (homes, school, and park building). When a secure outdoor backyard (sampling height 3 ft, no more than 10 ft from the home) was not available, sampling lines for micro-Aeths were extended 1 m out of second-floor window (n=2; sampling height 20 ft) or placed on roof decks (n=2; sampling heights 13 and 30 ft). Sampling location distances from the highway (I-95) ranged from 90 to 800 m.

We recorded characteristics of the participant's home or workplace for each sampling day, including (1) housing type (number of shared walls); (2) distance between traffic to house front; (3) location of sampler; (4) presence of (and distance to) nearby industrial or point sources (such as bus depots, manufacturing facilities, or construction sites; the technician was given a checklist of possible sources developed based on knowledge of the neighborhood and instructed to look for indicators of emissions); and (5) presence of cigarette smoke at or nearby the residence. We confirmed with participants that open burning or outdoor cooking did not take place at or near the premises during the monitoring day.

In addition, we calculated the ratio of measured BC to ambient $PM_{2.5}$. Ambient concentrations of $PM_{2.5}$ on monitoring days reflect hourly average concentrations measured by a beta-attenuation monitor at Philadelphia's Air Management Services Laboratory monitoring station located 4 km northwest of the study area. Hourly wind speed, direction, and temperature data came from Northeast Philadelphia Airport, which is 12 km northeast of Port Richmond. The wind rose in Fig. 2 shows wind direction and wind speed. Downwind conditions at the study sites was true for only 7 h of the total measurement time during the study. However, it is important to note that predominant wind direction throughout the year at the study site is upwind and therefore upwind measurements may more accurately represent typical pollution exposure.

Traffic counts

The Delaware Valley Regional Planning Commission Traffic conducted 14-class traffic counts using pneumatic tubes on E Allegheny Ave (both eastbound and westbound) and Richmond St (both northbound and southbound) for nine continuous days between 8 am on May 28 and 7 am on June 6, 2012. Eastbound traffic tubes on E Allegheny Ave did not remain fastened and therefore counts are unreliable on this roadway section and are not considered in data analysis. The pneumatic tube counter is capable of distinguishing between vehicle types (by number and spacing of axels), which can be used to distinguish between diesel and non-diesel vehicle class.

Statistical analysis

We completed data analyses using SAS (version 9.3; SAS Institute, Cary, NC), ArcGIS (version 10.1, ESRI, Inc., Redlands, CA), and IGOR Pro (version 6.2, WaveMetrics, Inc., Lake Oswego, OR). We used descriptive statistics to summarize temporal variability in pollutant concentrations and traffic counts. In addition, we used linear mixed effects models to assess for impact of hypothesized sources with BC levels, while controlling for correlation of measurements collected repeatedly at fixed locations.

First, we examined correlation among dependent and independent (predictor) variables to lessen problems with colinearity in data analysis. Only one of the variables with correlation ≥0.7 was used in the same multiple regression model. Next, we estimated parameters of mixed effects models using the SAS procedure PROC MIXED. We analyzed daily and hourly BC concentrations separately. We estimated linear mixed effects models on an aggregated "daily" data set with one averaged measurement per location (n=26). Micro-Aeths produced 1-min BC concentrations. We calculated boxcar averages at a 30-min frequency for each sampling day and location. We then calculated the average, median, minimum, and maximum of these 30-min averages and these served as dependent variables. We found BC concentrations to have a skewed distribution, and residuals in the regression analysis were heteroscedastic unless a log-transformation was applied. A lognormal assumption about levels of air pollution is also reasonable because such quantities cannot be zero and have occasional "high" values. Independent variables included day and location, and distance from transportation routes. In mixed effect models, "fixed" effect variables represent all levels or values from the variable of interest, and "random" effect variables represent random sample values drawn from a larger population of values. In this data set, we defined day and location as random effects with compound symmetry covariance structure, and defined transportation routes as fixed effects. Table 1 contains descriptive statistics of the variables in this data set.

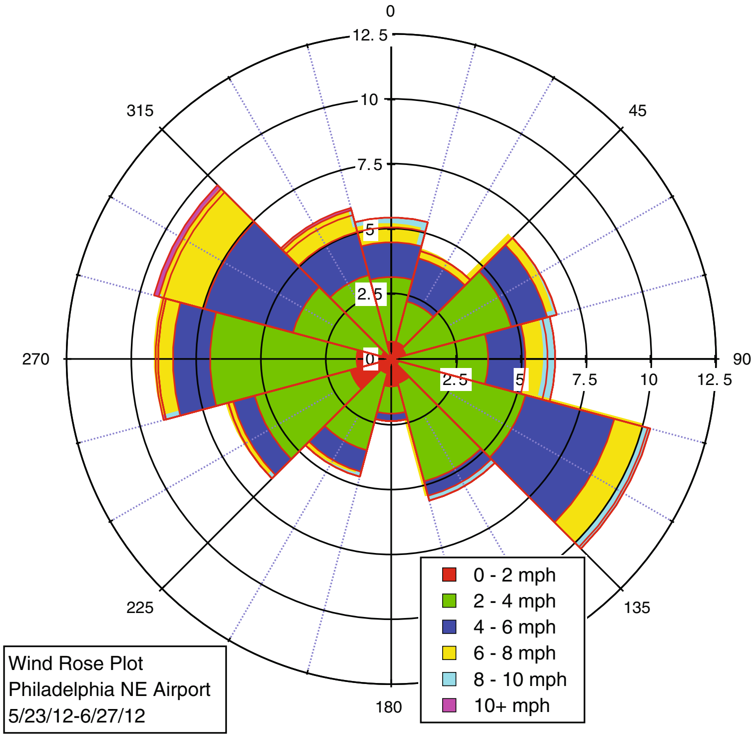

Fig. 2 Wind rose with wind speed at NE Philadelphia Airport

We then estimated linear mixed effects models on a disaggregated data set ("hourly"; n=79). The dependent variable consisted of 79 log-transformed hourly BC median and maximum concentrations for each micro-Aeth unit on monitoring days 2 through 4 (days on which traffic counts occurred). Independent variables included distance from transportation routes, traffic counts, time, wind direction, wind speed, and temperature (see Tables 1 and 2 for more details). We treated locations and days as random effects with compound symmetry covariance structure. This is a simple form that accounts for within and between-cluster correlation. Based on evaluation using fit statistics, our data did not support more complex models (e.g., AR(1) which

Table 1 Dependent and independent variables for aggregated daily measure data set (n=26)

		Min	Q1	Median	Q3	Max
Dependent variables[a]						
BC Average		0.4	0.7	1.1	1.6	3.8
BC Median		0.4	0.6	0.9	1.4	3.7
BC Minimum		0.2	0.4	0.5	0.7	1.6
BC Maximum		0.6	1.3	2.2	3.7	12.0
Independent variables						
Distance to (m):	I-95	93	236	363	421	1172
	Richmond St	4	234	249	306	1204
	E Allegheny Ave	3	296	835	964	1127

Q1 and Q3 indicate 25th and 75th percentiles, respectively

[a] Based on 30-min boxcar averages, in $\mu g\ m^{-3}$

reflects correlation in time and space), likely because of smallness of our dataset. Table 2 contains descriptive statistics of the variables in this data set.

We first conducted "univariate analyses," in which we examined effects of each of the predictor variables separately. If a predictor had a significant effect ($p<0.05$) on BC concentration, then it was retained in a multivariable model. The Akaike Information Criterion (AIC) (Akaike 1974) and Bayesian Information Criterion (BIC) (Schwarz 1978) served as test statistics for the purpose of model selection to account for both model complexity and fit in selecting the most parsimonious predictive model. When comparing models, the minimum AIC or BIC scores indicate the preferred model.

For both data sets, we found that inclusion of a random location parameter in PROC MIXED improved AIC/BIC fit statistics, compared to just having random effects. We then combined predictor variables found to be significant in univariate analyses in a multivariable model, with traffic count, distance, and the interaction between these and meteorology variables as main effects. This interaction reflected the fact that meteorological conditions modify the effect of sources of BC rather than generating BC. We looked for variables that maintained significant effect, and multivariable models that improved model fit according to AIC/BIC scores.

Table 2 Dependent and independent variables for disaggregated hourly measure data set (n=79)

		Min	Q1	Median	Q3	Max
Dependent Variables[a]						
BC Average		0.3	0.6	0.8	1.2	3.6
BC Median		0.2	0.4	0.7	0.9	2.2
Independent Variables						
Wind Speed (meters/s)		1.5	2.6	3.6	5.1	8.8
Wind Direction (degrees of compass)		10	230	280	300	360
Temperature (°C)		14	19	22	25	33
Distance[b]						
Traffic Counts[c]:						
Richmond St	Diesel traffic	0	3	10	28	60
	Non-Diesel traffic	26	128	290	374	598
	Combined	29	129	300	401	624
E Allegheny Ave[d]	Diesel traffic	0	2	4	12	25
	Non-Diesel traffic	12	118	224	322	478
	Combined	12	121	248	333	493

Q1 and Q3 indicate 25th and 75th percentiles, respectively

[a] Based on hourly boxcar averages in μg m^{-3}

[b] Distance measures same as in Table 1, in meters

[c] 60-min totals based on 24-h counts between May 29 – June 6, 2012

[d] Counts for eastbound traffic only due to counter malfunction in westbound direction

We first tested for correlation among independent and dependent variables using Pearson correlation coefficients. In the aggregated "daily" data set (n=26), among independent variables, we found significant ($p<0.05$) correlation between median and average measures of BC concentration (0.96), minimum and median measures (0.93), and minimum and average measures (0.86). Therefore, we assumed that median serves as a proxy for average and minimum measures. We also found significant correlation among distance to I-95 and Richmond St variables (0.91; these corridors parallel one another). We therefore removed I-95 from our model and assumed that distance to Richmond St serves as a proxy to distance to both Richmond St and I-95.

In the disaggregated "hourly" data set (n=79), we found correlation between average and median hourly concentrations and therefore use median concentration as the dependent variable. Significant correlation existed between diesel and non-diesel counts for Richmond St. and combined traffic counts. Because diesel is a known source of BC, we used diesel counts (combined and Richmond St) in our models. In addition, to avoid artificial difference between wind direction of 0° and 360°, we created a "downwind" binary variable representing upwind or downwind conditions (between 90° and 220°).

Results

Ae-51 duplicate intercomparison results

Figure 3 shows a regression comparison of the four micro-Aeths, and indicates that all units measured values within 20 % of the average measured value with high correlation. Micro-Aeth 4, which differs the most from the average value, experienced pump failure after the second monitoring day (May 29th). Data from this unit is included for days 1 (May 23) and 2 (May 29), but not subsequent monitoring days.

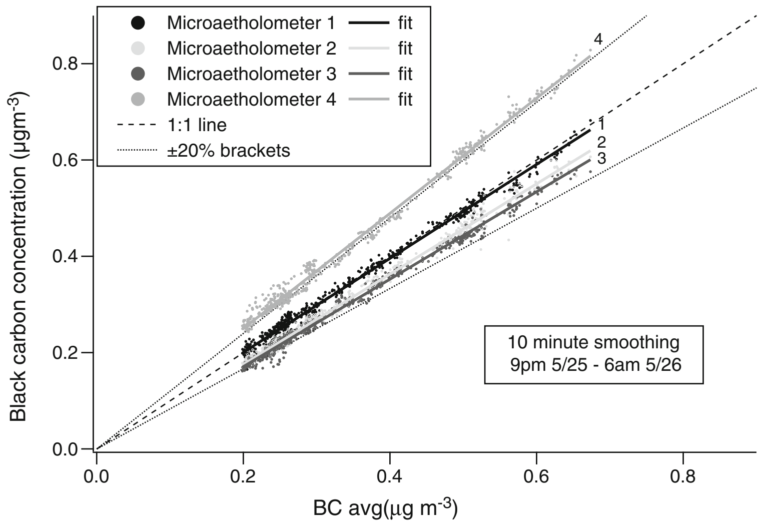

Fig. 3 Micro-Aethalometer comparison to black carbon (*BC*) average during duplicate testing, 9 pm 5/25/12 to 6 am 5/26/12

Micro-Aeth readings indicated high variability on several duplicate test days. The most extreme values corresponded with instrument alerts, such as signals out of range or overheating, so these data points were omitted from our analysis. However, there was sometimes substantial variability even without these alerts. The trace of BC oscillated considerably (up to± 45 μg m^{-3}) when the measured attenuation rose in a single "step" instead of steadily. Possible reasons include true variance of the concentration, shadow effects, or vibration of the instrument. However, when the trace oscillated but there was no "instrument alert," smoothed or averaged concentration values were still within reasonable expectation of BC concentrations.

Field measurement results

Daily 30-min average BC concentration was 1.2 μg m^{-3}, with a geometric mean (GM) of 1.1 μg m^{-3} and geometric standard deviation (GSD) of 1.7. Figure 4 shows median hourly BC concentration (and 25th and 75th percentiles), as well as 15-min traffic counts, by hour of day. The figure shows that BC concentrations exhibited diurnal variability, and on average were higher during a.m. hours. This is likely due to increased ground level emissions in the morning, and reduced dispersion due to boundary layer effects before daytime vertical mixing has occurred (Olofson et al. 2009; Allen et al. 1999). Univariate fixed effect estimates supported a significant negative effect of the time of day on BC maximum concentrations ($p<0.0001$; see Table 3).

Figure 4 also indicates a bimodal traffic pattern, with morning peak between 7 and 8 am, and evening peak between 4 and 6 pm. Hourly average count was 561 vehicles combined on E Allegheny Ave and Richmond St (GM=498; GSD =1.8). Diesel traffic was a small proportion of overall traffic; and on average accounted for 5 % of overall traffic. Traffic counts revealed a daily peak in the proportion of diesel to non-diesel traffic between the hours of 4 am and 8 am (up to 35 % on E Allegheny Ave).

Figure 5 shows hourly ambient $PM_{2.5}$ concentrations and the ratio between ambient $PM_{2.5}$ and measured BC. BC to ambient $PM_{2.5}$ ratios in general reflected the impact of diesel emissions to the total $PM_{2.5}$; they ranged from 0.01 to 0.4 (average 6 %) and varied diurnally. On monitoring days, hourly average ambient $PM_{2.5}$ concentration was 17.4 μg m^{-3} (GM= 15.5 μg m^{-3}, GSD=1.6 μg m^{-3}). Figure 5 reveals that $PM_{2.5}$ tended to peak in the a.m., and the BC to $PM_{2.5}$ ratio showed higher values in the morning when primary emissions were high. This ratio peaked when PM levels were relatively low and BC levels relatively high compared to study duration. As will be described below, statistical analyses show (based on collected data) that on an hour-by-hour basis, primarily time of day and location-based attributes including proximity to high-traffic roadways account for higher BC levels. Wind direction was entirely upwind on these days, which is typical for the study area on a year-round basis.

Site-to-site variation was more pronounced than day-to-day variation. Based on estimates from the linear

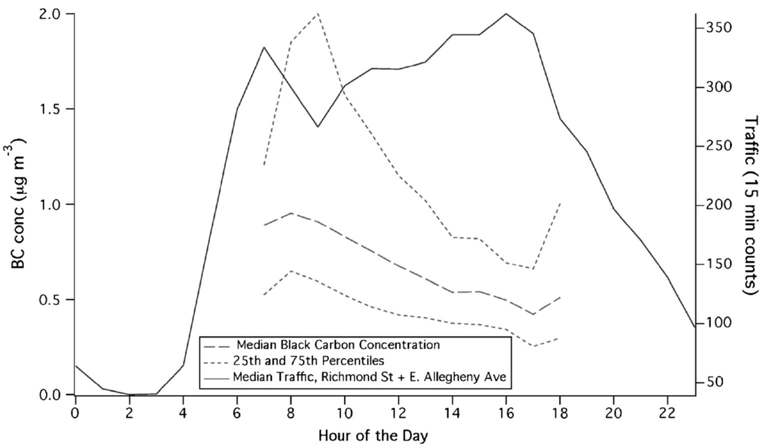

Fig. 4 Traffic counts vs. median black carbon concentrations using binomial smoothing of 15-min bins

mixed effects model, we found that day-to-day differences accounted for 28 % of the variance in BC concentration (maximum 30-min average), compared to a 72 % effect of site-to-site variation. Between-location variances were the only ones that were consistently different from zero in empty (Table 3) and multivariate models (Table 4); the estimate of variance exceeded its standard error. By contrast, there was no between-day variance that was distinguishable from statistical noise in these models.

Table 3 Estimates from univariate linear mixed effect models of hourly BC concentration (median hourly BC average)

Variables	SD	Variance parameters						Fixed effect estimates			% Change in BC	AIC	BIC
		Between day		Between location		Residual							
		σ^2	SE	σ^2	SE	σ^2	SE	$\hat{\beta}$	SE	*P*			
Empty model		0.06	0.07	0.02	0.01	0.02	0.004					−38	−40
Distance to:													
I-95	728.0	0.07	0.08	0.02	0.02	0.02	0.004	−3E-05	0.0002	0.9	−3 %[a]	−23	−25
Richmond St	798.9	0.05	0.06	0.02	0.02	0.02	0.004	0.0002	0.0002	0.3	21 %[a]	−23	−26
E Allegheny Ave	1284.0	0.04	0.05	0.02	0.01	0.02	0.004	0.0001	0.0001	0.2	10 %[a]	−22	−25
Diesel traffic:													
All	14.4	0.06	0.06	0.02	0.01	0.02	0.004	0.005	0.002	0.04	18 %[b]	−32	−34
Richmond St	35.2	0.02	0.04	0.02	0.01	0.02	0.004	0.002	0.001	0.01	21 %[b]	−31	−34
Weather:													
Wind direction	92.8	0.07	0.07	0.02	0.01	0.02	0.004	0.0002	0.0002	0.3	4 %[c]	−23	−26
Wind speed	4.4	0.05	0.05	0.02	0.01	0.02	0.004	−0.04	0.01	0.01	−33 %[d]	−38	−41
Temp	3.7	0.14	0.14	0.02	0.01	0.02	0.003	−0.03	0.01	<0.0001	−25 %[e]	−57	−60
Time	3.4	0.03	0.02	0.02	0.01	0.03	0.003	−3E-02	4E-03	<0.0001	−7 %[f]	−67	−67

SD Standard Deviation; *SE* Standard Error of the estimate; σ^2 variance; $\hat{\beta}$ Estimate

[a] Per 500 m distance from each roadway

[b] Per SD of predictor

[c] Per 90° from true north

[d] Per 1 m/s increase in wind speed

[e] Per °C increase in temperature

[f] Per hour from 8 am

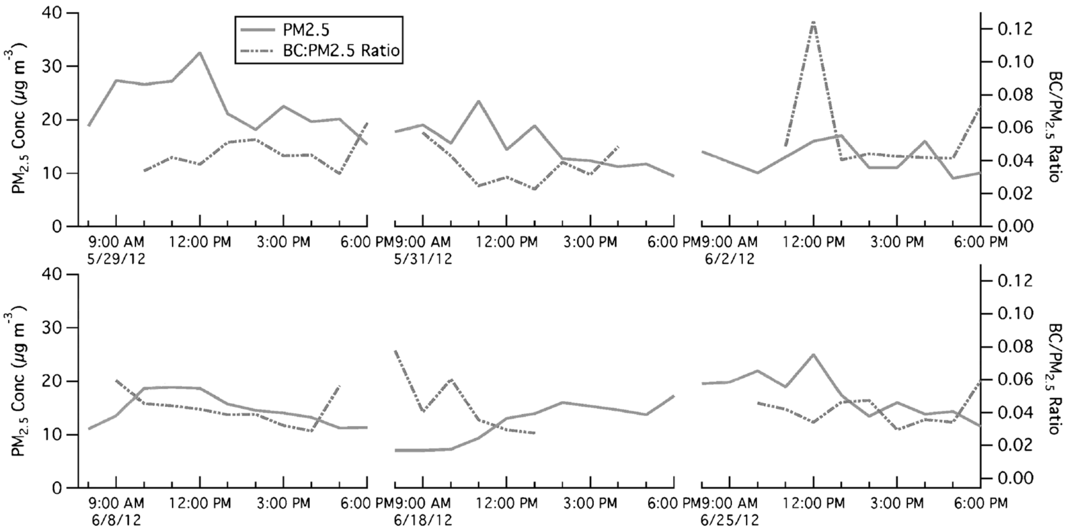

Fig. 5 Daily $PM_{2.5}$ and black carbon to $PM_{2.5}$ ratio

Table 3 shows univariate fixed effect estimates, or effect estimates for each predictor variable, performed on the hourly disaggregated data set (including diesel traffic counts, wind speed, temperature, and time). We derived these estimates by applying linear mixed effect models separately for each independent variable with hourly BC concentration. The AIC/BIC scores indicate model performance, with minimum number indicating the best fit. Results indicate that diesel traffic measures (including traffic counts and distance to highly trafficked roadways) explained with mixed results variation in BC concentrations. Univariate fixed effects models on hourly median BC concentration on days 2 through 4 showed some effect of traffic, but greater association between weather (wind speed and temperature) and time. Time had the greatest association with BC concentrations.

Conversion of the fixed effect estimates based on standard deviations of variables capturing fixed effects showed that increases in wind speed, temperature, and time of day resulted in 16, 12, and 10 % decrease in hourly median BC concentration, respectively. These relationships are expected based on atmospheric process of midday boundary mixing (Olofson et al. 2009). Table 4 shows multivariate fixed effect estimates, which

Table 4 Fixed effect estimates from multivariate linear mixed effect models of hourly BC concentration (median hourly BC average)

Variance parameters		Combined model			
Between day	σ^2	0.06			
	SE	0.05			
Between location	σ^2	0.02			
	SE	0.01			
Residual	σ^2	0.02			
	SE	0.003			
AIC		−59.4			
BIC		−65.7			
Fixed effects estimates			All diesel traffic	Richmond diesel traffic	Richmond diesel traffic * temp.
		$\widehat{\beta}$	0.004	0.01	0.001
		SE	0.002	0.00	0.0001
		P	0.14	<0.0001	<0.0001

SE Standard Deviation; *SE* Standard Error of the estimate; σ^2 variance; $\widehat{\beta}$ Estimate; *P p* value, or the probability that the observed estimate of the fixed effect ($\widehat{\beta}$) is different from zero simply by chance tested for combined effects of significant predictors found in univariate analyses on the hourly data set. A comparison of p values for each factor indicates that diesel traffic counts are significant predictors of BC concentrations; the probability that observed estimates of fixed effects different from zero was due to chance alone was less than 0.001.

One potential reason for mixed results of local traffic effects is the predominance of upwind conditions during the study, which is typical at the study site. On the majority of monitoring days, major traffic sources (I-95 and Richmond St) were not upwind of residential monitoring areas in Port Richmond. In addition, wind speed was low during downwind conditions, between stagnant to 6 m/s.

Despite prevalence of upwind conditions, we found that distance to arterials (primarily Richmond St) and I-95 were predictors of between-location variance in univariate mixed effects models on the daily, aggregated, dataset (results not shown). Most notably, we found that I-95 (or sources colocated with I-95) had the strongest effect. Distance to I-95 explained 61 % of the between-location variance of median 30-min average BC concentrations, and 66 % of the between-location variance of maximum 30-min average BC concentrations. Our data showed a 20 % decrease in 30-min median and 37 % decrease in 30-min maximum BC concentrations with every 500-m increase in distance from I-95.

Discussion and conclusions

This study represents a community-based effort to characterize black carbon concentrations in a Philadelphia neighborhood, and its relationship with associated predictors of this pollution. Measurements over 9 sampling days had a daily 30-min average BC concentration of 1.2 $\mu g\ m^{-3}$, with a maximum of 12 $\mu g\ m^{-3}$. These levels are typical of urban concentrations in the USA (U.S. Environmental Protection Agency 2010).

Diesel traffic is a constant presence and annoyance in Port Richmond. We witnessed and heard from participants that diesel trucks are travelling frequently on neighborhood collector streets. Our counts on major arterials showed that diesel truck traffic accounted for up to 35 % of all traffic during morning rush hour. Our data shows an effect of diesel traffic volumes on BC concentrations, but does not explain all variability on BC concentrations. Fixed effects models on hourly median BC concentration showed some effect of traffic, but greater impact of weather (wind speed and temperature) and time. Time showed the greatest relationship with BC concentrations of all study predictors. This could be an artifact of reduced a.m. dispersion due to boundary layer effects (Olofson et al. 2009; Allen et al. 1999). It could also be a factor of wet deposition and the hygroscopicity of black carbon particles that could be affected by humidity levels (Liu et al. 2012), and this is worth investigating in future research.

We also found that BC concentration varied more by location than by day. Distance to traffic arterials (primarily Richmond St) and I-95 were the identified predictors of this between-location variance in univariate analyses of the daily aggregated dataset. However, due to the prevalence of upwind conditions at monitoring locations, we are unable to say that traffic from I-95 and Richmond Ave are the only source of higher concentrations in their proximity: confounding by contribution from sources unidentified in our analysis may bias this effect of distance to traffic arterials. For example, our data show a 20 % decrease in median BC concentration and 37 % decrease in maximum BC concentration with every 500-m increase in distance from I-95 (converted from log-transformed to untransformed). We do not see an effect of distance from Allegheny Ave, likely because the vast majority of traffic moving through the neighborhood is on I-95 and Richmond Ave.

These results indicate that variation in location-based sources, including but not limited to diesel traffic emissions, are more important drivers of BC concentrations in Port Richmond neighborhood, compared to sources of daily variation such as weather events. At the same time, mixed effects model results showed that distance to the roadway does not help explain median BC concentration when traffic is included in the model. We interpret this to mean that distance to Richmond St does not affect BC concentration when there is little or no traffic.

BC to $PM_{2.5}$ ratios averaged around 6 %, which is similar to what other urban studies have found. These ratios were higher in a.m. hours during morning rush hour, when primary emissions were high. BC to $PM_{2.5}$ ratios decreased in the afternoon due to secondary aerosol formation processes.

Lack of traffic counts on all monitoring days, and malfunction of traffic counters on westbound E Allegheny Ave are limitations to this study. And although upwind conditions are typical in the study area, another limitation is the prevalence of upwind conditions during the study. This may have contributed to the lack of significance of wind direction in statistical models, which has a known physical effect on atmospheric dispersion. Placement of a weather station in the study area would have benefitted the study.

It may also be possible that our predictor variables—traffic and distance to roadways—were proxies for other sources, and that we did not account for other predictors in our models. We therefore cannot conclude that black carbon concentrations in Port Richmond are only influenced by diesel traffic volumes and distance to major roadways. In addition, because our study occurred during summer time during daytime hours, the statistical relationships found may not be representative of other seasons in the study area. Additional measurements during other times of the year would be beneficial to our understanding of spatiotemporal patterns of BC in Port Richmond. The statistical relationships found in our study are also not necessarily applicable to other areas due to differences in source types, traffic volumes, topography and morphology, and meteorology.

Although this study measured black carbon levels that are typical of urban concentrations in the USA, Port Richmond asthma rates are higher than city and national averages. This indicates a more complex relationship, which could include interference of other natural or anthropogenic aerosols, or exposure to stress relating to air pollution and its sources, poverty or other urban stressors. A more detailed study which adequately measures and quantifies known associations between exposure to pollutants, and other social stressors, is required to assess the real effect of black carbon.

Our study represents a community-driven collaborative effort to measure air pollution in an urban community heavily affected by goods movement. Study results have been shared with study participants, with a diesel workgroup that includes members from industry and regulatory agencies, and with community civic groups. Results have also been covered in a local newspaper.

This community-engaged study has lead to broader community awareness of typical air pollution levels in Port Richmond, and sources of this pollution. One implication that is of concern to residents is that spatial variation in BC concentration will also mean that exposure levels, and inherent health risks, may vary across the neighborhood as a function of time of day, weather patterns, diesel traffic volume, distance to traffic sources, and potentially other sources. While the community is interested to know more about links between exposure and health effects, they are in the mean time taking action to reduce exposure by promoting enforcement of anti-idling ordinances, no-truck route designations, and other policy solutions. Awareness of study process and findings has also raised awareness among industry and regulatory officials of local concerns regarding air pollution and desire to monitor for pollutants of concern beyond the NAAQS criteria pollutants. It has also opened discussions about further and broadened collaborations to measure and mitigate air pollution in the Philadelphia region.

Acknowledgments We would like to thank the Port Richmond community for partnering with us on this research endeavor. This research would not have been possible without the assistance of Peter DeCarlo and Michael Waring at Drexel University, Kyle Thompson at Missouri Science and Technology, Kathleen Ward Brown, and willingness to share instrumentation from Jon Levy at Boston University. This research has been made possible through funding by the United States Environmental Protection Agency (CARE 2 and Environmental Justice Small Grant to Clean Air Council), the Penn Genome Frontiers Institute, and a grant with the Pennsylvania Department of Health (Kondo). The Department of Health specifically disclaims responsibility for any analyses, interpretations, or conclusions. This work was also supported by the National Institutes of Health (grant R01AA020331; C. Branas), and unnamed funding from the United States Department of Agriculture, Forest Service. The National Institutes of Health and USDA had no role in the design and conduct of the study; collection, management, analysis, and interpretation of data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

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