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Influential factors affecting black carbon trends at four sites of differing distance from a major highway in Las Vegas

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Abstract

Elevated air pollution levels adjacent to major highways are an ongoing topic of public health concern worldwide. Black carbon (BC), a component of particulate matter (PM) emitted by diesel and gasoline vehicles, was measured continuously via a filter-based light absorption technique over ~ 16 months at four different stations positioned on a perpendicular trajectory to a major highway in Las Vegas, NV. During downwind conditions (winds from the west), BC at 20 m from the highway was 32 and 60% higher than concentrations at 100 and 300 m from the roadway, respectively. Overall highest roadside (20-m site) BC concentrations were observed during the

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time period of 4 a.m.–8 a.m. under low-speed variable winds ($3.02 \mu\text{g}/\text{m}^3$) or downwind conditions ($2.84 \mu\text{g}/\text{m}^3$). The 20-m site BC concentrations under downwind conditions are 85% higher on weekday periods compared to weekends during the time period of 4 a.m.–8 a.m. Whereas total traffic volume was higher on weekdays versus weekends and differed by approximately 3% on weekdays versus weekends, similarly, the detected heavy-duty fraction was higher on weekdays versus weekends and differed by approximately 21% on weekdays versus weekend. Low wind speeds predominated during early morning hours, leading to higher BC concentrations during early morning hours despite the maximum traffic volume occurring later in the day. No noticeable impact from the airport or nearby arterial roadways was observed, with the 300-m site remaining the lowest of the four-site network when winds were from the east. Multivariate linear regression analysis revealed that heavy-duty traffic volume, light-duty traffic volume, wind speed, weekday versus weekend, surface friction velocity, ambient temperature, and the background BC concentration were significant predictors of roadside BC concentrations. Comparison of BC and $\text{PM}_{2.5}$ downwind concentration gradients indicates that the BC component contributes substantially to the $\text{PM}_{2.5}$ increase in roadside environments. These results suggest that BC is an important indicator to assess the contribution of primary traffic emissions to near-road $\text{PM}_{2.5}$ concentrations, providing opportunities to evaluate the feasibility and effectiveness of mitigation strategies.

Introduction

Black carbon and $\text{PM}_{2.5}$ emissions: air quality impacts

Ambient concentrations of particulate matter, including particulate matter with aerodynamic diameter of $2.5 \mu\text{m}$ or less ($\text{PM}_{2.5}$) and $10 \mu\text{m}$ or less (PM_{10}), have been regulated internationally because of links to a number of adverse human health effects including cardiovascular, respiratory, and premature mortality occurrences (Breysse et al. 2013; Grahame and Schlesinger 2010). A recent meta-analysis (Rohr and Wyzga 2012) indicated that separately each major component of $\text{PM}_{2.5}$ is in some way responsible for adverse health impacts suggesting that total $\text{PM}_{2.5}$ concentration may not be solely responsible for adverse health effects. PM constituents such as carbonaceous materials may be significantly more important, including black carbon (BC), elemental carbon (EC), and organic carbon (OC). Janssen et al. (2011) indicates that BC is an important air quality metric when evaluating health risks from anthropogenic emission sources including highway vehicle emissions. In addition, risks for similar adverse health effects have been reported for populations living, working, and going to school near major roadways (Breysse et al. 2013; Franklin et al. 2008; Grahame and Schlesinger 2010; HEI 2010; U.S. EPA 2012). Although these associations have been identified, the particular contribution of PM or other near-road pollutants to adverse health effects has yet to be identified (U.S. EPA 2009; U.S. EPA 2012). Thus, there is particular interest in the spatial and temporal variability and composition of PM pollutant concentrations unique to the near-road environment to help elucidate the factors associated with exposure to PM and assessment of these exposures. With a large worldwide population spending significant time near large roadways, including as much as 16% of the US population living within 100 m (300 ft) of a four-or-more lane highway (U.S. Census Bureau 2007; U.S. EPA 2010), the public health implications are likely significant.

Air quality impacts from traffic

Traffic-related air pollution consists of thousands of gaseous and particulate compounds (HEI 2007; HEI 2010). Major gaseous pollutants emitted by motor vehicles include carbon monoxide (CO), oxides of nitrogen (NO, NO₂, NO_x), and mobile source air toxics (MSATs) such as benzene and toluene. Motor vehicles also emit PM in a combination of different sizes and compositions. PM with an aerodynamic diameter $\geq 10 \mu\text{m}$ is referred to as PM₁₀, while PM with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ in diameter is referred to as PM_{2.5}. PM coarse (PM_{10-2.5}) is defined as the difference between PM₁₀ and PM_{2.5}. PM can be composed of numerous materials, such as OC, EC, or BC, and inorganic metals (HEI 2010). Field measurements have shown elevated concentrations of BC and PM of varied composition near large roadways (see meta-analyses by Karner et al. 2010 and Zhou and Levy 2007). These field studies report that the concentrations and spatial gradients are influenced by roadway type, traffic volume, and meteorology (Baldauf et al. 2008; Fujita et al. 2014; Liang et al. 2013; McAdam et al. 2011) as well as diurnal and seasonal variations (Baldwin et al. 2015; Gordon et al. 2012; Hu et al. 2009; Kendrick et al. 2015; Kozawa et al. 2009; Polidori and Fine 2012; Zhu et al. 2004; Zhu et al. 2006). Understanding the spatial and temporal characteristics of total PM (i.e., PM₁₀, PM_{2.5}, PM_{Coarse}) and its constituents, namely BC, near large roadways provide insights on public health concerns.

BC contribution to near-road PM_{2.5}

As noted above, PM_{2.5} is composed of EC—an indicator of fossil fuel combustion including gasoline and diesel fuel combustion from highway vehicles and OC—an indicator of fossil fuel combustion and biomass burning. BC includes both EC—primarily formed pollutant and OC—primarily and secondarily formed pollutant (HEI 2010; Seinfeld and Pandis 2012). Multiple studies have reported differing contributions of BC to PM_{2.5}. For example, Venkatachari et al. (2006) reported the contribution of BC to PM_{2.5} at two New York City measurement sites to be 13 and 11%. Ruellan and Cachier (2001) reported the contribution of BC to PM_{2.5} for a Paris, France measurement site to be approximately 20%. Cao et al. (2009) and Tiwari et al. (2013) reported the average BC to PM_{2.5} contribution to be 8.3 and 5.3%, respectively. A study conducted in six Brazilian cities report the average BC to PM_{2.5} contribution in the range of 15–40% (Andrade et al. 2012; de Miranda et al. 2012). As reported by Andrade et al. (2012) and de Miranda et al. (2012), the average BC to PM_{2.5} contribution in São Paulo, Brazil was to be approximately 38%. Other studies conducted in Bangkok, Thailand (Hung et al. 2014) and Istanbul, Turkey (Ozdemir et al. 2014) have also reported high contributions of BC to PM_{2.5} in the range of 30–37%. These high contributions of BC to PM_{2.5} are probably due to multiple factors: (1) Bangkok, Istanbul, and São Paulo are considered megacities—population > 10 million, (2) existence of industrial facilities in the urban area, (3) vehicle fleet mix, and (4) vehicle engine technologies as well as on-road vehicle emission control technologies utilized in these cities.

Near-road study

The study described in this paper has multiple unique characteristics including duration of more than 1 year, site-specific meteorological and traffic data, and measurement of multiple air pollutant species. This paper focuses on analysis of BC and PM_{2.5} concentrations and

characteristics collected from December 2008 to April 2010 to evaluate spatial and meteorological effects of PM pollutants on potential population exposures in a near-road environment.

Methods

Study design and location

Air quality measurements were collected during a study from December 15, 2008 to April 21, 2010 in Las Vegas, NV for multiple particulates and gaseous pollutants as part of a collaborative effort between the US Department of Transportation's Federal Highway Administration (FHWA) and the EPA. Kimbrough et al. (2013b) describe the complete set of parameters measured during the study. The parameters relevant to this paper include continuous measurements of BC and PM_{2.5}, wind speed, and wind direction. The results presented in this analysis are a subset of extensive gaseous, particulate, meteorological, and traffic data collected over the study period, as part of a multi-site near-road study described previously (Kimbrough et al. 2013a; Kimbrough et al. 2013b; Kimbrough et al. 2014).

Sampling was conducted along a north-south stretch of Interstate-15 (I-15) at four locations (Fig. S1, Supplemental Information (SI)) along an east-west transect approximately perpendicular to the highway: 135 m west (historical upwind direction), 25 m east (historical downwind direction), 115 m east, and 300 m east of the highway (Kimbrough et al. 2013b). These four locations are referenced herein as nominal distances of – 100 m west, 20 m east, 100 m east, and 300 m east. Additional study location and design details are provided in SI and as described in Kimbrough et al. (2013b). A map of the study site as well as meteorological characteristics as measured at the Las Vegas McCarran International Airport are shown in Figs. S1, S2, and S3 (SI).

Traffic data

Traffic data were provided by the Nevada Regional Transportation Commission (RTC). The Nevada RTC used Wavetronix radar units and logged the data every 15 min (Table S1, SI). The radar units were located in the vicinity of the near-road measurement sites between the I-15/I-215 interchange and the I-15/Russell Road interchange. These units reported total traffic volume, vehicle speed, and vehicle type (light-duty vs. heavy-duty) based on length characteristics (Kimbrough et al. 2013b).

For this analysis, we assumed that vehicles with a length of 0–30 f. (ft) are light-duty vehicles, including passenger cars, sport utility vehicles (SUVs), and light-duty trucks. Vehicles > 30 ft. in length are assumed to be medium to heavy-duty vehicles which include trucks over 10,000 lb. gross vehicle weight (GVW), and combination trucks over 26,000 lb. GVW. We also assumed that all light-duty vehicles are gasoline and all heavy-duty vehicles are predominately diesel, an assumption supported by default data used for MOVES2014 (U.S. EPA 2014). Diurnal profiles of total traffic volume, heavy-duty vehicle percentage, and light-duty vehicle percentage are shown in Figs. S4 and S5 (SI).

Nearby sources of particulate matter

A review of the 2008 National Emissions Inventory (NEI) point source data indicates that the largest particulate emissions source within an approximately 10-km radius of the study site was McCarran International Airport. The 300-m downwind site was located 430 m west of Las Vegas' McCarran International Airport (western property boundary). The inventory reports that the PM_{2.5} emissions from McCarran International Airport were approximately 60 t/year in 2007 (U.S. EPA 2008). Assuming that the emissions are evenly distributed throughout a calendar year, this would equate to approximately 330 lb./day of PM_{2.5} being emitted by airport operations. The ground activities at the airport were located approximately 5 km from the study location, although aircraft take off and landings occurred approximately 1 km away. Zhu et al. (2011) reported elevated PM_{2.5} levels (37.1 µg/m³) relative to background (14.3 µg/m³) due to airport activity. However, the source sample site for the PM_{2.5} measurements was located at the blast fence, 140 m from an aircraft's takeoff position. As reported by Hudda et al. (2014) and Hudda and Fruin (2016), the downwind spatial extent of particle number concentrations and size distributions from aircraft activity may be more significant than previously thought—at least 18 km distant and downwind of airport activities.

Other nearby transportation sources include Las Vegas Boulevard, approximately 200 m east of the 300-m downwind site, and a parking lot just south of the 100- and 300-m downwind sites. Las Vegas Boulevard supported approximately 50,000 vehicles/day at the time of the study. Measurements would have most likely been influenced during easterly wind flows. Deliveries to the Las Vegas Convention Center were staged out of the nearby paved parking lot and truck activity was highly variable. Impacts from the parking lot would be correspondingly variable. Easterly winds would most likely have the greatest impact on the measurement site. Impacts on PM concentrations from the airport would likely occur only during winds from the east. Lastly, Las Vegas is located in desert terrain. Minimal ground vegetation existed around the study sites, which may have impacted PM concentrations during high wind events, passing vehicles along the train tracks, or on nearby roads to the parking lot. Since the Las Vegas area is a PM₁₀ non-attainment area, Clark County Department of Air Quality and Environmental Management (DAQEM) has strict abatement regulations regarding fugitive dust emissions (Clark County DAQEM 2015).

Results and discussion

Near-road BC trends

In this analysis, we summarized the data by site to show concentration gradients for all BC observations (Fig. 1; Table 1). As reported in Kimbrough et al. (2013b), four wind direction categories were developed: downwind (winds from the west, 210°–330° and wind speeds 1 m/s), parallel (wind from the north/south, 150°–210°/330°–30° and wind speeds 1 m/s), upwind (winds from the east, 30°–150° and wind speeds 1 m/s), and variable (winds from all directions and speeds < 1 m/s).

BC concentrations for all wind conditions at the 20-m roadside site are 29, 57, and 42% higher than BC concentrations at the 100-m downwind, 300-m downwind, and – 100-m

upwind sites, respectively. The highest concentrations at the 20-m roadside and downwind sites occur during periods of variable wind conditions (i.e., low wind speeds) and downwind (winds from west) conditions. The greatest percent increase (38%) in BC concentration at the 20-m roadside site relative to the – 100-m upwind site occurs during parallel wind conditions (winds from north or south).

Weekday BC concentrations are higher than weekend concentrations. At the 20-m roadside site, weekday BC concentrations are approximately 52% higher versus the weekend during downwind (winds from west) conditions. During parallel wind conditions (winds from north or south), weekday BC concentrations are approximately 47% higher at the 20-m roadside site. Comparing across all sites during downwind conditions, weekday versus weekend, weekday BC concentrations are 47–66% higher. As shown in Fig. S4 (SI), weekday and weekend traffic volume is similar. However, the weekday percentage of heavy-duty trucks is higher (15–30%), suggesting that weekday BC concentrations at the measurement locations were significantly higher due to the influence of heavy-duty vehicle emissions (Figs. S4 and S5, SI). The spatial gradient is shown graphically in Fig. 1. These figures show that there is a significant difference in the weekday versus weekend BC concentration gradient that is likely due to the difference in heavy-duty traffic volume and the on-road diesel fleet mix which comprises a greater fraction of higher emitting heavy-duty trucks (i.e., diesel) during the weekday versus the weekend.

We analyzed the diurnal profile at each measurement site for differing wind conditions. By segregating the diurnal profile by differing wind conditions, it is apparent that the highest BC concentrations occur under specific meteorological and traffic conditions (Fig. S6, SI). The highest BC concentrations at the downwind sites (20-m roadside, 100-m downwind, 300-m downwind) occur during the morning hours of 4 a.m.–8 a.m. during downwind conditions. The average daily BC concentration at the 20-m roadside site under downwind conditions is $1.81 \mu\text{g}/\text{m}^3$. Comparing this concentration with the average BC concentration at the 20-m roadside site under downwind conditions for the hours of 4 a.m. to 8 a.m. ($2.84 \mu\text{g}/\text{m}^3$), the percent difference is approximately 44%. The highest absolute BC concentration at the 20-m site occurred from 6 a.m. to 7 a.m. ($3.45 \mu\text{g}/\text{m}^3$) with the percent difference between this value and the overall BC concentration under downwind conditions being approximately 62%. Filtering the data further shows the average BC concentration at the 20-m roadside site during a weekday under downwind conditions for the hours of 4 a.m. to 8 a.m. ($3.59 \mu\text{g}/\text{m}^3$) with the highest absolute BC concentration at the 20 m site occurring from 7 a.m. to 8 a.m. ($4.26 \mu\text{g}/\text{m}^3$). In comparison, the average BC concentration at the 20-m roadside site under downwind conditions during a weekend for the hours of 4 a.m. to 8 a.m. was approximately $1.44 \mu\text{g}/\text{m}^3$ with the highest absolute BC concentration ($1.73 \mu\text{g}/\text{m}^3$) at the 20-m site occurring from 7 a.m. to 8 a.m. For the percent difference between the average weekday and weekend BC concentrations from 4 a.m. to 8 a.m., downwind conditions is approximately 85%. Downwind conditions prevail during these hours along with low wind speeds ($< 2 \text{ m/s}$). High BC concentrations are shown to occur during variable wind conditions (all wind directions, low wind speeds). Concomitant with these meteorological conditions, traffic volume is shown to increase during this 4a.m. to 8a.m. time period (Fig. S4a).

Figure 2 shows the diurnal profile for each measurement site under wind conditions with the highest concentrations (downwind and variable) for weekday versus weekend. By segregating the diurnal profiles in this way, it becomes apparent that the highest BC concentrations occur during the week and under specific meteorological and traffic conditions. This analysis reinforces the assessment that there is a significant difference in the BC concentration gradient during the weekdays versus the weekend (Figs. 1 and 2) and the hypothesis that this difference is due to the difference in heavy-duty traffic volume and the on-road fleet mix that comprises a greater fraction of higher emitting heavy-duty trucks (i.e., diesel) during the weekdays versus the weekend.

We further examined the data for the hours of 4 a.m.–8 a.m. based on a review of the diurnal traffic volume profile and the diurnal profile of the percent of heavy-duty traffic (Figs. S4 and S5; Table S2, SI). The spatial gradient profile (Fig. 3) indicates the influence of variable wind conditions and downwind conditions on BC concentrations. Meteorological conditions are important factors relative to these high BC concentrations: (1) lower wind speeds, (2) winds predominantly from the west to the southwest, (3) decreased atmospheric mixing overnight extending into the early morning hours, and (4) higher fraction of heavy-duty vehicle traffic occurring during these early morning hours.

Figure S7 (SI) shows a polar plot of BC concentrations by season and measurement site. A summary of these data is shown in Table S3 (SI) and Fig. S8 (SI). The data show that the fall and winter seasons have slightly higher annual average BC concentrations at the site west of I-15, most likely due to the high frequency of downwind conditions as well as variable wind conditions. When we inspect the differing wind conditions segregated by season, the highest BC concentrations at the 20-m roadside site occur during variable wind conditions (i.e., less turbulent atmospheric mixing conditions). Recall that variable wind conditions are defined as winds from all directions and < 1 m/s wind speed. The summer season has the highest BC concentration at the 20-m roadside site ($2.83 \mu\text{g}/\text{m}^3$) during variable wind conditions, while the winter and fall seasons have the higher BC concentrations at the 20-m roadside site during downwind conditions (winds from west), 2.04 and $1.99 \mu\text{g}/\text{m}^3$, respectively. The highest BC concentrations at the 100-m downwind site occur during the summer season and under variable conditions followed by high BC concentrations that occur during the fall and winter seasons under variable wind conditions. The highest BC concentrations at the 300-m downwind site occur during the spring and summer during variable wind conditions. The highest BC concentrations at the -100 -m upwind site occur during the summer season and fall seasons and under variable wind conditions. The implication is that the -100 -m upwind site is being impacted by vehicle emissions from the highway as well as other nearby sources such as McCarran International Airport.

A spatial gradient plot by season is shown in Fig. S9 (SI). This plot also shows higher BC concentrations during the summer season. Additionally, the plot clearly shows that during periods of variable winds, BC concentrations are higher at all four measurement locations.

Near-road BC contributions to $\text{PM}_{2.5}$

We also analyzed a subset of BC and $\text{PM}_{2.5}$ data collected from December 1, 2009 to February 19, 2010, in an effort to quantify the contribution of BC to the overall $\text{PM}_{2.5}$

concentrations. This period coincided with the logging of valid continuous PM_{2.5} data. Summaries of PM_{2.5} and BC mass averages and confidence intervals based on continuous measurements are shown in Table 2 for all wind conditions and downwind conditions only (winds from west, 210°–330°).

As shown in Table 2, PM_{2.5} and BC spatial gradient concentration decay can be observed, although the spatial gradient decay is less pronounced than for gaseous pollutants as reported in Kimbrough et al. (2013b). The spatial gradient concentration decay for PM_{2.5} is also shown in Fig. S10 (SI). As reported from a study conducted in Burlington, Ontario, Canada by McAdam et al. (2011), there may be several reasons why this may occur: (1) vehicle fleet mix—higher number of diesel trucks, including more PM entrained road dust from heavy-duty diesel vehicles or more BC emissions from these vehicles or both; (2) vehicle contribution to both primary and secondary PM_{2.5}; (3) distribution of primary and secondary PM_{2.5} in ambient air is different; and (4) background concentrations of PM_{2.5}. Canagaratna et al. (2010) reported that an additional factor that may cause PM_{2.5} and BC spatial gradient concentration decay to be less pronounced than for gaseous pollutants may be the presence of high background oxygenated organic aerosols (OOA). Field studies conducted in Portland, OR by Kendrick et al. (2015) and in Largo, MD by Ginzburg et al. (2015) reported that PM_{2.5} concentrations are not well correlated with traffic volumes.

Figure 4 shows bivariate plots for BC versus heavy-duty traffic volume and BC/PM_{2.5} ratio versus heavy-duty traffic volume during downwind conditions, weekdays, and weekend for the 20-m roadside site. These plots suggest that there is a stronger relationship for BC versus heavy-duty traffic volume (Fig. 4, left) than for BC/PM_{2.5} ratio versus heavy-duty traffic volume (Fig. 4, right). The greatest contribution of BC to the overall PM_{2.5} concentration appears to be from heavy-duty traffic. The scatter observed in Fig. 4 may be due to additional factors influencing the concentration at the 20-m roadside site during downwind conditions. These factors are most likely variations in wind speed, heavy-duty traffic volume, and heavy-duty fleet mix—presence of higher emitting heavy-duty vehicles.

These results are consistent with other studies that have reported moderate correlations between heavy-duty traffic and BC concentrations (i.e., elevated BC concentrations during high traffic volumes) and weak correlations between heavy-duty traffic and PM_{2.5} concentrations (i.e., minor increase if any in PM_{2.5} concentrations over background during high traffic volumes). Several studies that have shown moderate to strong correlations between heavy-duty traffic and BC concentrations include Baldauf et al. (2008), Wang et al. (2009), and Westerdahl et al. (2009). Baldauf et al. (2008) showed a moderate correlation between heavy-duty traffic and BC concentrations probably due to the low volume of heavy-duty traffic observed during the study. However, studies by Wang et al. (2009) and Westerdahl et al. (2009) showed strong correlations between heavy-duty traffic and BC concentrations probably due to the volume of heavy-duty traffic, vehicle fleet mix, and engine technologies.

Studies by Kendrick et al. (2015), Ginzburg et al. (2015), and Whitlow et al. (2011) found weak correlation or no correlation between heavy-duty traffic and PM_{2.5} concentrations. These studies included an urban arterial intersection location (Kendrick et al. 2015), a high

traffic freeway location (Ginzburg et al. 2015), and an urban arterial location (Whitlow et al. 2011). The studies by Kendrick et al. (2015) and Ginzburg et al. (2015) were longer duration studies and provide insight into a temporal component that most studies do not capture.

Data shown in Table 2 suggest that the overall contribution of BC to the $PM_{2.5}$ concentration is approximately 15–26% under all wind conditions and when winds are from the west (downwind conditions). The overall contribution of BC to the $PM_{2.5}$ is similar to results reported in previous studies—Venkatachari et al. (2006), Cao et al. (2009), and Tiwari et al. (2013). Other studies conducted in megacities—population > 10 million—have reported substantially higher contributions of BC to $PM_{2.5}$ in the range of 30–37% (Hung et al. 2014; Ozdemir et al. 2014).

Figure 5 shows mean concentrations (5—left panel) for $PM_{2.5}$ and BC for winds from west and normalized mean concentrations (5—right panel) for $PM_{2.5}$ and BC for winds from west. Mean concentrations for the – 100-m upwind, 100-m downwind, and 3000m downwind have been normalized to the 20-m roadside site. Normalized means for each site shown in Fig. 5 were calculated as follows: V_{PS}/V_{PS1} , where V = average value, P = pollutant, S = site, and $S1$ = site 1. During down wind conditions (winds from west), BC has a more pronounced spatial gradient relative to $PM_{2.5}$. McAdam et al. (2011) reported similar findings that may be explained by vehicle fleet mix, vehicle emissions contributing to both primary and secondary $PM_{2.5}$, differences in the distribution of primary and secondary $PM_{2.5}$ in ambient air, and background concentrations of $PM_{2.5}$. These results support the conclusion that BC is a more suitable surrogate indicator of vehicle emissions than $PM_{2.5}$.

Figure 6a,b shows polar plot concentrations for all sites for tapered element oscillating microbalance/filter dynamics measurement system (TEOM/FDMS) $PM_{2.5}$ and BC by wind speed and wind direction, respectively. The radial dimension for each polar plot is an indicator of wind speed (m/s). The further away from the center of the plot, the higher the wind speed. Figure 6a shows that while there is a significant contribution of $PM_{2.5}$ from the nearby highway, contributions from other sources can be observed. Figure 6b shows that the highest contribution of BC is predominantly from the nearby highway. Regardless of wind direction, each measured metric ($PM_{2.5}$ or BC) was always highest at the 20-m roadside site compared to the other study sites.

Influential factors in the near-road environment

Meteorology

As reported in Kimbrough et al. (2013b), four wind direction categories were developed: downwind (winds from the west, 210°–330° and wind speeds > 1 m/s), parallel (wind from the north/south, 150°–210°/330°–30° and wind speeds > 1 m/s), upwind (winds from the east, 30°–150° and wind speeds > 1 m/s), and variable (winds from all directions and speeds < 1 m/s).

Wind categories show diurnal trends. During the early morning hours of midnight to 6 a.m. and 6 p.m. to midnight, downwind (winds from west) conditions comprise approximately 50% of the time period, while winds blowing from the east transport particulate matter

across the highway to the – 100-m upwind site ~ 6% of the time (Fig. S3, SI). During the midday hours of 8 a.m. to 1 p.m., downwind conditions (winds from west) comprise approximately 12% of the time period. Upwind conditions dominated during this period of time (approximately 50%). As reported by Kimbrough et al. (2013b), this wind distribution results in the – 100-m upwind measurement site having a lesser impact from highway emissions relative to the measurement sites on the western side of I-15 during upwind (winds from east) conditions. Additionally, lesser impacts are observed at the 20-m roadside site relative to the other sites during the midday hours of 8 a.m. to 1 p.m. Intuitively, one might believe that these hours would have higher emissions at the 20-m roadside site due to higher annual average daily traffic observed during these hours. However, meteorological conditions suppress emission impacts from the highway at the 20-m site as upwind conditions prevail during the hours of 8 a.m. to 1 p.m. This wind flow pattern can lead to the – 100-m upwind site having higher near-road ambient air concentrations relative to the 20-m roadside site. As reported in Kimbrough et al. (2013b), when downwind conditions (winds from west) occur higher, near-road ambient air concentrations are more likely to be observed at the 20-m site versus the – 100-m upwind site on an annual average basis (Table 1).

Wind categories show seasonal trends. During all seasons, downwind (winds from west) conditions comprise approximately 38% of the time period, while winds blowing from the east, where winds transport across the highway to the – 100-m upwind site, occurs ~ 25% of the time, resulting in the – 100-m upwind measurement site having a lesser impact from highway emissions relative to the measurement sites on the western side of I-15 during upwind (winds from east) conditions. As reported in Kimbrough et al. (2013b), downwind conditions (winds from the west) occur more frequently and probably account for the higher near-road ambient air concentrations observed at the 100-m downwind site versus the – 100-m upwind site on an annual average basis (Table 1).

The meteorological data show that the average hourly wind speed during the overnight and early morning hours is approximately 2 m/s. These lower wind speeds combined with increasing traffic volume during early morning hours suggest higher near-road ambient concentrations due to overnight inversion conditions and decreased atmospheric mixing. However, higher wind speeds that occur during peak traffic times suggest lower near-road ambient concentrations due to increased atmospheric mixing. Other studies have reported similar results with regard to diurnal variations of meteorological conditions and the impact on near-road pollutant concentrations (Baldwin et al. 2015; Liang et al. 2013).

Las Vegas traffic

Average hourly traffic volume by weekday and weekend and the percent of heavy-duty traffic are shown in Fig. S4 (SI) for the study period. While traffic volume is similar during weekday versus weekend, increased weekend traffic volume has a later start time: 4 a.m. versus 3 a.m. for the weekday (Fig. S4, SI). In addition, there is a more gradual increase in traffic volume during the weekend versus weekday. Traffic volume during the weekend peaks at approximately noon while the weekday traffic peak occurs from 3 p.m. to 4 p.m. The percent of heavy-duty weekday traffic is higher versus percent of heavy-duty weekend traffic. The maximum fraction of heavy-duty traffic during the weekday is approximately

15–16% and occurs at approximately 5 a.m., while the maximum fraction of heavy-duty traffic during the weekend is approximately 12–13% and occurs between 5 a.m. and 6 a.m. (Fig. S4b, SI) for the study period. Figure S5 (SI) shows Las Vegas total traffic volume, percent light-duty vehicle traffic volume, and percent heavy-duty vehicle traffic volume by hour of the day.

Recent near-road studies have shown that there are diurnal variations in total traffic volume and weekday/weekend variations (Baldauf et al. 2008; Batterman et al. 2015; Ginzburg et al. 2015; Kendrick et al. 2015; Kozawa et al. 2009). Moreover, other studies have shown that there are diurnal variations in the fleet mix (i.e., light-duty versus heavy-duty volumes). These variations can result in significant differences in observed near-road air pollutant concentrations (Baldwin et al. 2015; Batterman et al. 2015; Ginzburg et al. 2015).

Regression modeling—near-road BC concentrations

To evaluate the influential factors impacting roadside BC concentrations, we ran multiple regression model routines using the linear model, `lm`, function from the R statistics package (R Development Core Team 2011). We used as the response (Y) variable the log (base 10) of measured BC at the 20-m roadside site [$\text{Log}_{10}(\text{BC})$] and as the model effects variables: total traffic volume; heavy-duty traffic volume—count of trucks (> 30 ft. in length); light-duty traffic volume—count of passenger vehicles (0–30 ft. in length); weekday/weekend—terms accounting for weekday versus weekend; wind speed; wind speed squared; mixing height of the surface boundary layer—taken as the maximum of the convective and mechanical mixing heights; surface friction velocity (u^*)—term describing wind shearing stress near the surface; ambient air temperature—temperature of ambient air; log of the measured BC at the – 100-m upwind measurement location [$\text{Log}_{10}(\text{BC_bkgd})$]; month; season, hour of day; surface roughness; and sensible heat flux. We began stepwise reduction of the predictors by evaluating the relative importance of each predictor and the correlation between predictors. At each step, we calculated the relative importance of the predictor by calculating the regression model performance based on three criteria: square of the residuals (R^2), root mean squared error (RMSE), and the Akaike Information Criterion (AIC). The first predictor eliminated was the wind speed-squared due to its high correlation with wind speed; eliminating wind speed-squared improved the R^2 and AIC. This model with 14 predictors gave the best overall performance of R^2 , RMSE, and AIC (Table S4, SI). We proceeded to eliminate unneeded predictors in a stepwise fashion based on a bootstrap method by their relative importance to R^2 , where R^2 , RMSE, and AIC were calculated at each step (Table S4, SI). As predictors were eliminated, we calculated the R^2 , RMSE, and AIC and monitored for significant decreases in R^2 and increases in RMSE and AIC. We found that there is a significant increase in RMSE and AIC when the seventh predictor, heavy-duty traffic volume, is eliminated from the model as shown in Table S4, SI. Thus, the seven-predictor model consisting of heavy-duty traffic volume, wind speed, weekday/weekend, frictional surface velocity [u^*], ambient temperature, log of background BC concentration [$\text{Log}_{10}(\text{BC_bkgd})$], and hour of day provides an efficient model with good model performance. We note that the heavy-duty vehicle volume predictor is the only direct emission term remaining in the model, so it could be inferred that heavy-duty traffic is the major source of BC emanating from the roadway beyond the background BC concentration.

An indirect emission term, the categorical weekday/weekend term, provides additional explanatory power vis-à-vis the differences in observed heavy-duty traffic volume on weekdays and weekends, as shown in Fig. S4 (SI). In addition, we can see in Fig. S4 (SI) that the hour of day term also plays an indirect role in the emissions, i.e., the heavy-duty diesel percentage is dependent on weekday versus weekend and the hour of day. However, this parameter is added to the model as a categorical variable because of its non-linear behavior in relation to heavy-duty traffic volume. In addition to the three emissions-related terms and background BC term, the other three predictors in the seven-predictor model are meteorological terms: wind speed, frictional surface velocity, and ambient temperature. We show the seven-predictor model performance predicting BC 20-m monitor concentrations in Fig. 7, where the monitor is in a downwind orientation from the roadway.

As shown in Fig. 7, the R^2 is 0.7474 and the root mean square error (RMSE) is 0.3131. From Table 1, the average BC concentration at the 20-m roadside site during downwind conditions is $1.81 \mu\text{g}/\text{m}^3$ and the predicted BC concentration at the 20-m roadside site during downwind conditions is $1.50 \mu\text{g}/\text{m}^3$ [Table 3, ($10^{\text{MeanofResponse}}$)]. The measured average BC concentration at the 20-m roadside site during downwind conditions differs by approximately 18% than the average predicted concentration which suggests that additional factors may be influencing the measured BC concentrations at the 20-m roadside site.

Parameter estimates in Table 3 show that heavy-duty traffic volume influences BC concentrations. However, weekday versus weekend has a greater impact. Heavy-duty trucks are large sources of BC and as shown in Fig. S4 (SI), the percent of heavy-duty weekday traffic is higher versus percent of heavy-duty weekend traffic. Light-duty traffic volume minimally impacts BC concentration as would be expected since light-duty vehicles are not large sources of BC.

As an additional step, we plotted the residuals of the parameters versus the residuals of $\log_{10}(\text{BC})$ for the 20-m roadside site. This plotting was done by eliminating the predictor from the seven-predictor model and showing the resulting residuals as a function of the eliminated predictor in Fig. S11 (SI). Residuals clustered around the zero line would indicate that the predictor does not have a strong explanatory power in the model. However, residuals that show a pattern as a function of a predictor would have strong explanatory power in the model. We see from Fig. S11 (SI) that the log of the background BC concentration has a strong pattern, so its inclusion in the model has a strong power to explain the BC concentration at the 20-m roadside site. We also see patterns in the residuals for the remaining parameters, so they also have explanatory power in the model. We also did this residual analysis for the predictors that were eliminated from the final seven predictor model by plotting the residuals from the seven-predictor model versus the eliminated predictors in Fig. S12 (SI). We can see that the eliminated predictors in Fig. S12 (SI) show residuals clustered around the zero line. Thus, we have confidence that the seven predictors selected—heavy-duty traffic volume, wind speed, weekday/weekend, frictional surface velocity [u^*], ambient temperature, log of background BC concentration [$\text{Log}_{10}(\text{BC_bkgd})$], and hour of day—are the most influential in predicting the 20-m roadside concentration.

Regression modeling—near-road BC/PM_{2.5} concentrations

To evaluate the influential factors impacting the BC/PM_{2.5} ratio, we use the linear model, `lm`, function from the R stats package. We used as the response (Y) variable the log (base 10) of measured BC/PM_{2.5} at the 20-m roadside site and as the model effects variables: heavy-duty traffic volume—count of trucks (> 30 ft. in length); light-duty traffic volume—count of passenger vehicles (0–30 ft. in length); weekday/weekend—terms accounting for weekday versus weekend; wind speed—speed of wind; wind speed squared; mixing height of the surface boundary layer—taken as the maximum of the convective and mechanical mixing heights; surface friction velocity (u^*)—term describing wind shearing stress near the surface; ambient air temperature—temperature of ambient air; log of the measured BC at the 100m upwind measurement location [$\text{Log}_{10}(\text{BC/PM}_{2.5_bkgd})$]; month; season, hour of day; surface roughness; and sensible heat flux. We began stepwise reduction of the predictors by evaluating the relative importance of each predictor and the correlation between predictors. At each step, we calculated the relative importance of the predictor by calculating the regression model performance based on three criteria: square of the residuals (R^2), root mean squared error (RMSE), and the Akaike Information Criterion (AIC). We used the same process for this set of model runs as in the previous section. From these multiple regression model runs, we determined that the best fit was achieved using a seven predictor model consisting of heavy-duty traffic volume, light-duty traffic volume, weekday/weekend, frictional surface velocity [u^*], log of background BC/PM_{2.5} concentration ratio [$\text{Log}_{10}(\text{BC/PM}_{2.5_bkgd})$], month, and hour of day. In comparison with the seven predictor model from the previous section, here the ambient temperature and wind speeds were not significantly explanatory. However, light-duty traffic volume and month of year were more explanatory to the BC/PM_{2.5} model. The omission of temperature and wind speed is due to BC and PM_{2.5} being subject to the same dispersion conditions. Therefore, their measured ratio is more dependent on the traffic composition on the roadway, thus the added explanatory power of light-duty traffic volume and month of year. The only remaining dispersion related meteorological parameter is the surface friction velocity, u^* . Modeling results indicate that the R^2 and the RMSE for the BC/PM_{2.5} ratio are 0.3465 and 0.2578. 0.2576, respectively (Fig. 8).

Modeling results shown in Table 4 indicate that heavy-duty traffic volume influences the BC/PM_{2.5} ratio. However, weekday versus weekend has a greater impact. The average measured BC/PM_{2.5} ratio for the 20-m roadside site under downwind conditions is 0.26, and the predicted BC/PM_{2.5} ratio for the 20-m roadside site under downwind conditions is 0.17 [Table 4, ($10^{\text{MeanofResponse}}$)]. The average BC/PM_{2.5} ratio at the 20-m roadside site during downwind conditions differs by approximately 42% than the average predicted concentration which suggests that BC is more important than PM_{2.5} as an indicator of air pollution from highway vehicles, and there may be additional factors influencing the BC/PM_{2.5} ratio at the 20-m roadside site.

Again as an additional step, we plotted the residuals of the parameters versus the residuals of $\text{log}_{10}(\text{BC/PM}_{2.5})$ for the 20-m roadside site. This plotting was done by eliminating the predictor from the seven-predictor model and showing the resulting residuals as a function of the eliminated predictors in Fig. S13 (SI). Residuals clustered around the zero line would

indicate that the predictor does not have a strong explanatory power in the model. However, residuals that show a pattern as a function of a predictor would have strong explanatory power in the model. We see from Fig. S13 (SI) that the month of the year has a strong pattern, so its inclusion in the model has strong power to explain the BC/PM_{2.5} ratio at the 20-m roadside site. We also see patterns in the residuals for the remaining parameters, so they also have explanatory power in the model. We also did this residual analysis for the predictors that were eliminated from the final seven predictor model, by plotting the residuals from the seven-predictor model versus the eliminated predictors in Fig. S14 (SI) pattern. Thus, we have confidence that the seven predictors selected—heavy-duty traffic volume, light-duty traffic volume, weekday/weekend, frictional surface velocity [u^*], log of background BC/PM_{2.5} concentration ratio [$\text{Log}_{10}(\text{BC}/\text{PM}_{2.5}\text{_bkgd})$], month, and hour of day—are the most influential in predicting the 20-m roadside BC/PM_{2.5} ratio.

Conclusions

Analysis of measurement data indicates that the highest overall BC concentrations occur during the morning hours, from 4 a.m. to 8 a.m. in all wind directions and on weekdays and weekends. These morning hours are typically periods of low variable wind speeds and when winds are oriented across the roadway toward the monitoring location, when decreased atmospheric mixing is most likely to occur and there is a higher heavy-duty vehicle percentage on the roadway. These effects are exaggerated on weekdays when the heavy-duty vehicle percentage is nearly 1.5 times the percentage on weekends. Increased atmospheric mixing throughout the middle hours of the day dilutes the concentrations during peak traffic periods. In addition, there is a lower percentage of heavy-duty vehicles during the middle and later parts of the day. These significant differences in BC concentration on weekdays versus weekends and morning peak versus the rest of the day emphasize the difference in emission of BC between light-duty (mainly gasoline) and heavy-duty (mainly diesel) vehicles.

The highest BC concentrations at all sites occur in the summer during variable wind conditions most likely due to less turbulent atmospheric mixing conditions—less atmospheric dilution. The lowest concentrations at the downwind sites occur when winds are oriented across the roadway away from the monitors (i.e., winds from the east). A concentration gradient is observed indicating upwind influence of the roadway in these conditions.

The minimal spatial concentration gradient decay for the PM mass measurements suggests the influence of other PM sources not related to traffic fuel combustion on the highway as well as secondary PM_{2.5} formations.

These results suggest that BC may better represent impacts from primary PM emissions from traffic, especially heavy-duty vehicles, while PM mass measurements likely represent a combination of traffic emissions, entrained road dust, local source influences, and background concentrations in complex urban areas. In addition, characterization of the heavy-duty diesel fleet fraction is important to the understanding of near-road BC concentrations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Andrade MF, de Miranda RM, Fornaro A, Kerr A, Oyama B, de Andre PA et al. (2012) Vehicle emissions and PM_{2.5} mass concentrations in six Brazilian cities. *Air Qual Atmos Health* 5:79–88. 10.1007/s11869-010-0104-5 [PubMed: 22408695]
2. Baldauf R, Thoma E, Hays M, Shores R, Kinsey J, Gullett B et al. (2008) Traffic and meteorological impacts on near-road air quality: summary of methods and trends from the Raleigh near-road study. *J Air Waste Manag Assoc* 58:865–878. 10.3155/1047-3289.58.7.865 [PubMed: 18672711]
3. Baldwin N, Gilani O, Raja S, Batterman S, Ganguly R, Hopke P et al. (2015) Factors affecting pollutant concentrations in the near-road environment. *Atmos Environ* 115:223–235. 10.1016/j.atmosenv.2015.05.024
4. Batterman S, Cook R, Justin T (2015) Temporal variation of traffic on highways and the development of accurate temporal allocation factors for air pollution analyses. *Atmos Environ* 107:351–363. 10.1016/j.atmosenv.2015.02.047
5. Breyse PN, Delfino RJ, Dominici F, Elder ACP, Frampton MW, Froines JR et al. (2013) US EPA particulate matter research centers: summary of research results for 2005–2011. *Air Qual Atmos Health* 6:333–355. 10.1007/s11869-012-0181-8
6. Canagaratna MR, Onasch TB, Wood EC, Herndon SC, Jayne JT, Cross ES et al. (2010) Evolution of vehicle exhaust particles in the atmosphere. *J Air Waste Manag Assoc* 60:1192–1203. 10.3155/1047-3289.60.10.1192 [PubMed: 21090548]
7. Cao J-J, Zhu C-S, Chow JC, Watson JG, Han Y-M, Wang G-h et al. (2009) Black carbon relationships with emissions and meteorology in Xi'an, China. *Atmos Res* 94:194–202. 10.1016/j.atmosres.2009.05.009
8. Carslaw DC, Ropkins K (2012) Openair—an R package for air quality data analysis. *Environ Model Softw* 27–28:52–61. 10.1016/j.envsoft.2011.09.008
9. Clark County DAQEM (2015) Clark County Air Quality Home Page. Clark County Department of Air Quality & Environmental Management. <http://www.clarkcountynv.gov/depts/AirQuality/Pages/default.aspx>. Accessed 17 Sept 2015
10. de Miranda RM, de Fatima Andrade M, Fornaro A, Astolfo R, de Andre PA, Saldiva P (2012) Urban air pollution: a representative survey of PM_{2.5} mass concentrations in six Brazilian cities. *Air Qual Atmos Health* 5:63–77. 10.1007/s11869-010-0124-1 [PubMed: 22408694]
11. Franklin M, Koutrakis P, Schwartz P (2008) The role of particle composition on the association between PM_{2.5} and mortality. *Epidemiology* 19:680–689 [PubMed: 18714438]
12. Fujita EM, Campbell DE, Arnott WP, Johnson T, Ollison W (2014) Concentrations of mobile source air pollutants in urban microenvironments. *J Air Waste Manag Assoc* 64:743–758. 10.1080/10962247.2013.872708 [PubMed: 25122949]

13. Ginzburg H, Liu X, Baker M, Shreeve R, Jayanty RKM, Campbell D et al. (2015) Monitoring study of the near-road PM_{2.5} concentrations in Maryland. *J Air Waste Manag Assoc* 65:1062–1071. 10.1080/10962247.2015.1056887 [PubMed: 26067547]
14. Gordon M, Staebler RM, Liggio J, Li S-M, Wentzell J, Lu G et al. (2012) Measured and modeled variation in pollutant concentration near roadways. *Atmos Environ* 57:138–145. 10.1016/j.atmosenv.2012.04.022
15. Grahame TJ, Schlesinger RB (2010) Cardiovascular health and particulate vehicular emissions: a critical evaluation of the evidence. *Air Qual Atmos Health* 3:3–27. 10.1007/s11869-009-0047-x [PubMed: 20376169]
16. HEI (2007) Mobile-source air toxics: a critical review of the literature on exposure and health effects. Health Effects Institute, Boston URL: <http://pubs.healtheffects.org/view.php?id=282>
17. HEI (2010) Traffic-related air pollution: a critical review of the literature on emissions, exposure, and health effects. Health Effects Institute, Boston URL: <https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health>
18. Hu S, Fruin S, Kozawa K, Mara S, Paulson SE, Winer AM (2009) A wide area of air pollutant impact downwind of a freeway during pre-sunrise hours. *Atmos Environ* 43:2541–2549. 10.1016/j.atmosenv.2009.02.033
19. Hudda N, Fruin SA (2016) International airport impacts to air quality: size and related properties of large increases in ultrafine particle number concentrations. *Environ Sci Technol* 50:3362–3370. 10.1021/acs.est.5b05313 [PubMed: 26971965]
20. Hudda N, Gould T, Hartin K, Larson TV, Fruin SA (2014) Emissions from an international airport increase particle number concentrations 4-fold at 10 km downwind. *Environ Sci Technol* 48:6628–6635. 10.1021/es5001566 [PubMed: 24871496]
21. Hung NTQ, Lee S-B, Hang NT, Kongpran J, Kim Oanh NT, Shim S-G et al. (2014) Characterization of black carbon at roadside sites and along vehicle roadways in the Bangkok Metropolitan Region. *Atmos Environ* 92:231–239. 10.1016/j.atmosenv.2014.04.011
22. Janssen NA, Hoek G, Simic-Lawson M, Fischer P, van Bree L, ten Brink H et al. (2011) Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM₁₀ and PM_{2.5}. *Environ Health Perspect* 119:1691–1699. 10.1289/ehp.1003369 [PubMed: 21810552]
23. Karner AA, Eisinger DS, Niemeier DA (2010) Near-roadway air quality: synthesizing the findings from real-world data. *Environ Sci Technol* 44:5334–5344. 10.1021/es100008x [PubMed: 20560612]
24. Kendrick CM, Koonce P, George LA (2015) Diurnal and seasonal variations of NO, NO₂ and PM_{2.5} mass as a function of traffic volumes alongside an urban arterial. *Atmos Environ* 122:133–141. 10.1016/j.atmosenv.2015.09.019
25. Kimbrough S, Baldauf R, Hagler G, Shores RC, Mitchell W, Whitaker DA et al. (2013a) Long-term continuous measurement of near-road air pollution in Las Vegas: seasonal variability in traffic emissions impact on local air quality. *Air Qual Atmos Health* 6:295–305. 10.1007/s11869-012-0171-x
26. Kimbrough ES, Baldauf RW, Watkins N (2013b) Seasonal and diurnal analysis of NO₂ concentrations from a long-duration study conducted in Las Vegas, Nevada. *J Air Waste Manag Assoc* 63:934–942. 10.1080/10962247.2013.795919 [PubMed: 24010374]
27. Kimbrough S, Palma T, Baldauf RW (2014) Analysis of mobile source air toxics (MSATs)—near-road VOC and carbonyl concentrations. *J Air Waste Manag Assoc* 64:349–359. 10.1080/10962247.2013.863814 [PubMed: 24701693]
28. Kozawa KH, Fruin SA, Winer AM (2009) Near-road air pollution impacts of goods movement in communities adjacent to the Ports of Los Angeles and Long Beach. *Atmos Environ* 43:2960–2970. 10.1016/j.atmosenv.2009.02.042
29. Liang MS, Keener TC, Birch ME, Baldauf R, Neal J, Yang YJ (2013) Low-wind and other microclimatic factors in near-road black carbon variability: a case study and assessment implications. *Atmos Environ* 80:204–215. 10.1016/j.atmosenv.2013.07.057

30. McAdam K, Steer P, Perrotta K (2011) Using continuous sampling to examine the distribution of traffic related air pollution in proximity to a major road. *Atmos Environ* 45:2080–2086. 10.1016/j.atmosenv.2011.01.050
31. Ozdemir H, Pozzoli L, Kindap T, Demir G, Mertoglu B, Mihalopoulos N et al. (2014) Spatial and temporal analysis of black carbon aerosols in Istanbul megacity. *Sci Total Environ* 473–474:451–458. 10.1016/j.scitotenv.2013.11.102 [PubMed: 24388901]
32. Polidori A, Fine PM (2012) Ambient concentrations of criteria and air toxic pollutants in close proximity to a freeway with heavy-duty diesel traffic. *South Coast Air Quality Management District*. URL: <http://www.aqmd.gov/docs/default-source/air-quality/air-quality-monitoring-studies/near-roadway-study.pdf?sfvrsn=2>
33. R Development Core Team (2011) R: a language and environment for statistical computing, 2.13.1 edn R Foundation for Statistical Computing, Vienna
34. Rohr AC, Wyzga RE (2012) Attributing health effects to individual particulate matter constituents. *Atmos Environ* 62:130–152. 10.1016/j.atmosenv.2012.07.036
35. Ruellan S, Cachier H (2001) Characterisation of fresh particulate vehicular exhausts near a Paris high flow road. *Atmos Environ* 35:453–468. 10.1016/S1352-2310(00)00110-2
36. Seinfeld JH, Pandis SN (2012) *Atmospheric chemistry and physics: from air pollution to climate change*, 2nd edn. John Wiley and Sons, Inc., Hoboken
37. Tiwari S, Srivastava AK, Bisht DS, Parmita P, Srivastava MK, Attri SD (2013) Diurnal and seasonal variations of black carbon and PM_{2.5} over New Delhi, India: influence of meteorology. *Atmos Res* 125–126:50–62. 10.1016/j.atmosres.2013.01.011
38. U.S. Census Bureau (2007) American Housing Survey for the United States: 2007. <http://www.census.gov/prod/2008pubs/h150-07.pdf>. Washington, D.C. 20,401
39. U.S. EPA (2008) National Emissions Inventory. <https://www.epa.gov/air-emissions-inventories/2008-national-emissions-inventory-nei-data>. Accessed 19 Oct 2016
40. U.S. EPA (2009) Integrated Science Assessment (ISA) for particulate matter (Final Report, Dec 2009). EPA/600/R-08/139F, 2009. Washington, DC
41. U.S. EPA (2010) Primary National Ambient Air Quality Standards for nitrogen dioxide (75 FR 6474, February 9, 2010) codified in 40 CFR parts 50 and 58. <https://www3.epa.gov/ttn/naaqs/standards/nox/fr/20100209.pdf>. Accessed 8 April 2017
42. U.S. EPA (2012) Report to Congress on black carbon EPA-450/R-12-001. <https://www3.epa.gov/airquality/blackcarbon/2012report/fullreport.pdf>. Accessed 17 Nov 2015 Washington, DC
43. U.S. EPA (2014) MOVES (Motor Vehicle Emission Simulator). <http://www3.epa.gov/otaq/models/moves/>. Accessed 16 Nov 2015
44. Venkatachari P, Zhou L, Hopke PK, Felton D, Rattigan OV, Schwab JJ et al. (2006) Spatial and temporal variability of black carbon in New York City. *J Geophys Res Atmos* 111:D10S05. 10.1029/2005JD006314
45. Wang X, Westerdahl D, Chen LC, Wu Y, Hao J, Pan X et al. (2009) Evaluating the air quality impacts of the 2008 Beijing Olympic Games: on-road emission factors and black carbon profiles. *Atmos Environ* 43:4535–4543
46. Westerdahl D, Wang X, Pan X, Zhang KM (2009) Characterization of on-road vehicle emission factors and microenvironmental air quality in Beijing, China. *Atmos Environ* 43:697–705. 10.1016/j.atmosenv.2008.09.042
47. Whitlow TH, Hall A, Zhang KM, Anguita J (2011) Impact of local traffic exclusion on near-road air quality: findings from the New York City “Summer Streets” campaign. *Environ Pollut* 159:2016–2027. 10.1016/j.envpol.2011.02.033 [PubMed: 21429643]
48. Zhou Y, Levy J (2007) Factors influencing the spatial extent of mobile source air pollution impacts: a meta-analysis. *BMC Public Health* 7:89 10.1186/1471-2458-7-89 [PubMed: 17519039]
49. Zhu Y, Hinds W, Shen S, Sioutas C (2004) Seasonal trends of concentration and size distribution of ultrafine particles near major highways in Los Angeles. *Aerosol Sci Technol* 38:5–13. 10.1080/02786820390229156
50. Zhu Y, Kuhn T, Mayo P, Hinds WC (2006) Comparison of daytime and nighttime concentration profiles and size distributions of ultrafine particles near a major highway. *Environ Sci Technol* 40:2531–2536. 10.1021/es0516514 [PubMed: 16683588]

51. Zhu Y, Fanning E, Yu RC, Zhang Q, Froines JR (2011) Aircraft emissions and local air quality impacts from takeoff activities at a large international airport. *Atmos Environ* 45:6526–6533. 10.1016/j.atmosenv.2011.08.062

Fig. 1.

BC spatial gradient for differing wind conditions for full data set from December 2008 to April 2010: (left) weekday, (middle) weekend, and (right) all days

Fig. 2.

Diurnal profile for each measurement site: (top left) weekday—downwind conditions (winds from west); (top right) weekday—variable winds; (bottom left) weekend—downwind conditions (winds from west); and (bottom right) weekend—variable wind conditions. The gray bars are meant to highlight the hours of 4 a.m.–8 a.m.

Fig. 3.
BC spatial gradient plot for the time period of 4 a.m.–8 a.m.

Fig. 4. Bivariate plot for 20-m roadside site for downwind conditions, weekday (red circles), weekend (blue triangles). **a** BC concentration versus heavy-duty traffic volume. **b** BC/PM_{2.5} ratio versus heavy-duty traffic volume

Fig. 5.

Concentration and normalized concentration plots for continuous PM_{2.5} and BC data: (left panel) concentration—winds from west, (right panel) normalized concentrations—winds from west. Data normalized to 20-m roadside site. Normalized means for each site shown in normalized concentrations (right panel) were calculated as follows: V_{PS}/V_{PS1} , where V = average value, P = pollutant, S = site, and $S1$ = site 1

Fig. 6. Polar plot mean concentrations for all sites **a** $\text{PM}_{2.5}$ and **b** BC by wind speed and wind direction. For each polar plot, the radial dimension is an indicator of wind speed (m/s). Farther away from the center of the plot, the wind speed is higher. Plots generated using openair an R package (Carslaw and Ropkins 2012)

Fig. 7. Regression results for 20-m roadside site under downwind conditions. Log₁₀ (BC actual) (i.e., measured) versus predicted at 20-m roadside site under downwind conditions—December 15, 2008 to April 21, 2010. Weekdays are represented by red circles; weekends are represented by blue triangles

Fig. 8.

Regression results for 20-m roadside site under downwind conditions. Log (BC/PM_{2.5} ratio actual) versus Log (BC/PM_{2.5} ratio predicted)—December 1, 2009 to February 19, 2010. Weekdays are represented by red circles; weekends are represented by blue triangles

Table 1.

Summary of BC data by measurement location, weekday, weekend, and wind conditions—long-term, 5-min averages at each measurement location—time span December 15, 2008 to April 21, 2010

BC ($\mu\text{g}/\text{m}^3$)													
Wind conditions	– 100-m upwind (site 4)			20-m roadside (site 1)			100-m downwind (site 2)			300-m downwind (site 3)			Avg. h. traffic volume
	N	Avg.	95% CI ^a	N	Avg.	95% CI ^a	N	Avg.	95% CI ^a	N	Avg.	95% CI ^a	
All	11,783	0.97	0.96–0.99	11,319	1.49	1.47–1.52	10,418	1.11	1.09–1.13	10,084	0.83	0.81–0.84	6878
Downwind	4288	0.88	0.85–0.91	4157	1.81	1.77–1.85	3815	1.31	1.28–1.35	3703	0.97	0.95–1	5991
Parallel	4912	0.78	0.76–0.8	4675	1.15	1.13–1.18	4296	0.81	0.79–0.83	4061	0.58	0.56–0.6	7268
Upwind	1509	1.27	1.23–1.31	1446	1.03	0.99–1.07	1365	0.84	0.81–0.88	1361	0.67	0.64–0.7	8591
Variable	1074	1.82	1.75–1.89	1041	2.42	2.33–2.5	942	2.04	1.97–2.12	959	1.53	1.47–1.58	6166
Weekday													
All	8423	1.09	1.07–1.12	8151	1.68	1.65–1.71	7442	1.24	1.22–1.26	7204	0.92	0.9–0.94	6933
Downwind	3068	0.99	0.95–1.02	2987	2.05	2–2.09	2714	1.48	1.44–1.52	2612	1.11	1.07–1.14	6022
Parallel	3516	0.87	0.85–0.9	3378	1.29	1.26–1.32	3086	0.90	0.87–0.93	2927	0.64	0.62–0.66	7337
Upwind	1081	1.42	1.36–1.47	1048	1.12	1.07–1.17	977	0.92	0.87–0.97	982	0.72	0.69–0.76	8654
Variable	758	2.08	2.00–2.17	738	2.76	2.65–2.87	665	2.32	2.23–2.42	683	1.72	1.65–1.79	6251
Weekend													
All	3360	0.67	0.65–0.69	3168	1.02	1.00–1.04	2976	0.78	0.76–0.8	2880	0.59	0.57–0.61	6740
Downwind	1220	0.61	0.58–0.64	1170	1.20	1.17–1.24	1101	0.90	0.87–0.94	1091	0.66	0.63–0.69	5915
Parallel	1396	0.53	0.5–0.55	1297	0.80	0.76–0.83	1210	0.58	0.55–0.61	1134	0.43	0.41–0.46	7095
Upwind	428	0.90	0.85–0.95	398	0.79	0.73–0.85	388	0.66	0.60–0.71	379	0.54	0.49–0.58	8435
Variable	316	1.20	1.13–1.27	303	1.59	1.50–1.67	277	1.38	1.29–1.46	276	1.05	0.98–1.11	5952

^aConfidence interval (CI)

Table 2

PM_{2.5} and BC concentrations and normalized concentrations—for all wind directions and winds from west (downwind) (December 1, 2009–February 19, 2010)

Site name	Distance from road	All wind directions			Winds from west (downwind)			All wind directions	Winds from west
		N	Avg	95% CI	N	Avg	95% CI		
PM _{2.5}									
Site 4	– 100-m upwind	546	8.58	8.21–8.95	256	8.89	8.31–9.47	0.85	0.80
Site 1	20-m roadside	546	10.07	9.63–10.51	256	11.10	10.49–11.72	1.00	1.00
Site 2	100-m downwind	546	8.49	8.15–8.82	256	9.43	8.93–9.92	0.84	0.85
Site 3	300-m downwind	546	8.46	8.11–8.81	256	9.35	8.82–9.88	0.84	0.84
BC									
Site 4	– 100-m upwind	546	1.19	1.13–1.26	256	1.18	1.09–1.27	0.70	0.58
Site 1	20-m roadside	546	1.71	1.61–1.80	256	2.04	1.90–2.18	1.00	1.00
Site 2	100-m downwind	546	1.39	1.31–1.47	256	1.67	1.55–1.80	0.81	0.82
Site 3	300-m downwind	546	1.12	1.05–1.18	256	1.35	1.25–1.45	0.65	0.66
BC/PM _{2.5} ratio									
Site 4	– 100-m upwind	546	0.17	0.15–0.2	256	0.18	0.14–0.22	0.71	0.69
Site 1	20-m roadside	546	0.24	0.20–0.27	256	0.26	0.20–0.32	1.00	1.00
Site 2	100-m downwind	546	0.18	0.17–0.19	256	0.19	0.18–0.21	0.75	0.73
Site 3	300-m downwind	546	0.15	0.14–0.17	256	0.16	0.15–0.18	0.63	0.62

TEOM/FDMS and BC data from all sites is from December 1, 2009 to February 19, 2010 for only those hours when all instruments were operating concurrently

Table 3.

Regression results for Log(BC) measured versus predicted at 20-m roadside site under downwind conditions

Summary of fit					
R^2		R^2 adjusted	Root mean square error	Mean of response	Observations (or sum Wgts)
0. 7474		0. 7454	0.1360	0. 1757	3687
Analysis of variance					
Source		DF	Sum of squares	Mean square	F value
Heavy-duty traffic volume		1	20.37	20.37	1029.89
Wind speed		1	62.42	62.42	3348.84
Weekday/weekend		1	29.31	29.31	1572.56
Surface friction velocity		1	0.97	0.97	51.86
Temperature		1	1.0	1.0	53.52
Log ₁₀ (BC_bkgd)		1	76.03	76.03	4079.14
Hour		23	11.57	0.50	26.99
Parameter estimates					
Term		Estimate	Std error	t value	Prob > t
Intercept		- 7.233e-01	7.743e-02	- 9.342	1.603e-20
Heavy-duty traffic volume	(HD)	4.003e-05	5.544e-06	7.220	6.286e-13
Wind speed		3.350e-02	5.390e-03	6.214	5.732e-10
Weekday/weekend	(wkdwke)	- 1.335e-01	5.284e-03	- 25.256	7.301e-130
Surface friction velocity	(ustar)	- 4.861e-01	5.762e-02	- 8.436	4.664e-17
Temperature		3.185e-03	2.576e-04	12.3656	1.938966e-34
Log ₁₀ (BC_bkgd)		4.172e-01	7.782e-03	53.612	0.000e + 00
Hour 2		1.105e-04	1.380e-02	0.008	9.936e-01
Hour 3		4.451e-02	1.364e-02	3.262	1.116e-03
Hour 4		1.206e-01	1.356e-02	8.893	9.174e-19
Hour 5		1.785e-01	1.366e-02	13.064	3.729e-38
Hour 6		2.106e-01	1.375e-02	15.3137	2.353e-51
Hour 7		2.029e-01	1.475e-02	13.7503	5.5249e-42
Hour 8		1.652e-01	1.677e-02	9.852	1.278e-22
Hour 9		1.650e-01	2.175e-02	7.586	4.172e-14
Hour 10		1.1367e-01	2.664e-02	4.266	2.039e-05
Hour 11		1.676e-01	2.528e-02	6.628	3.901e-11
Hour 12		1.748e-01	2.419e-02	7.227	5.981e-13
Hour 13		1.660e-01	2.132e-02	7.785	9.006e-15
Hour 14		1.947e-01	1.961e-02	9.925	6.296e-23
Hour 15		1.461e-01	1.838e-02	7.949	2.487e-15
Hour 16		1.528e-01	1.746e-02	8.750	3.205e-18
Hour 17		1.415e-01	1.655e-02	8.551	1.767e-17

Summary of fit					
R^2		R^2 adjusted	Root mean square error	Mean of response	Observations (or sum Wgts)
Hour 18		1.328e-01	1.545e-02	8.596	1.209e-17
Hour 19		9.367e-02	1.441e-02	6.500	9.080e-11
Hour 20		9.655e-02	1.338e-02	7.214	6.568e-13
Hour 21		8.548e-02	1.305e-02	6.551	6.501e-11
Hour 22		5.519e-02	1.293e-02	4.269	2.010e-05
Hour 23		2.648e-02	1.307e-02	2.026	4.284e-02
Hour 24		4.407e-03	1.329e-02	0.332	7.401e-01

Table 4.

Regression results for Log(BC/PM_{2.5} ratio) measured versus predicted at 20-m roadside site under downwind conditions

Summary of fit					
R^2		R^2 adjusted	Root mean square error	Mean of response	Observations (or sum Wgts)
0.35600		0.318266	0.25764	− 0.77534	543
Analysis of variance					
Source		DF	Sum of squares	Mean square	F value
Heavy-duty traffic volume		1	4.670	4.670	65.680
Light-duty traffic volume		1	3.025	3.025	42.5463
Weekday/weekend		1	0.281	0.2815	3.9588
Surface friction velocity		1	2.647	2.6468	37.2249
Log ₁₀ (BC/PM _{2.5} _bkgd)		1	1.888	1.8879	26.5523
Hour		23	3.182	0.1383	1.9456
Month		2	4.231	2.1156	30.0525
Parameter estimates					
Term		Estimate	Std error	t ratio	Prob > t
Intercept		− 5.092e−01	7.323e−02	− 6.9531	1.0942e−11
Heavy-duty traffic volume	(HD)	2.300e−04	1.085e−04	2.120	3.445e−02
Light-duty traffic volume	(LD)	− 2.500e−05	1.250e−05	− 1.200	4.604e−02
Weekday/weekend	(wkdwke)	− 6.119e−02	3.448e−02	− 1.774	7.661e−02
Surface friction velocity	(ustar)	− 2.146e−01	1.619e−01	− 1.326	1.854e−01
Log ₁₀ (BC/PM _{2.5} _bkgd)		2.227e−01	4.153e−02	5.363	1.243e−07
Hour 6		1.795e−01	8.692e−02	2.066	3.936e−02
Hour 7		1.699e−01	8.593e−02	1.977	4.862e−02
Month 2		5.029e−02	3.052e−02	1.648	1.000e−01
Month 12		− 2.334e−01	4.079e−02	− 5.722	1.789e−08