7-2015

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Sustainable Cities and Society 15 (2015) 64–74

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Pedestrian exposure to near-roadway $PM_{2.5}$ in mixed-use urban corridors: A case study of Omaha, Nebraska

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ARTICLE INFO

Article history:
Available online 15 December 2014

Keywords:
Pedestrian exposure
Fine particulate matter
Mixed-use development

ABSTRACT

Compact, mixed-use, and pedestrian-oriented urban developments may offer numerous environmental and health benefits, yet they may also facilitate pedestrian exposure to air pollution within the near-roadway environment. This research examines ambient concentrations of fine particulate matter ($PM_{2.5}$) across six sites situated within central Omaha, Nebraska, a mid-sized metropolitan area located in the Midwest US. The sites ranged from a low-density, strip-mall development to moderate-density entertainment, commercial, and retail districts with varying degrees of horizontal and vertical mixed-use. Tracing approximately two kilometer routes along the sidewalk, factors affecting average and peak $PM_{2.5}$ concentrations at each site were identified using a mobile data cart capable of simultaneously recording video and sampling $PM_{2.5}$. In general, sidewalk $PM_{2.5}$ concentrations, averaged for each outing, were similar to "background" values obtained at a nearby fixed monitoring station (FMS). The results of a linear regression analysis suggest that 56% of the variability in sidewalk $PM_{2.5}$ were attributable to background concentrations. Short-duration peak concentrations of up to 360 $\mu g\, m^{-3}$ were associated primarily with vehicle tailpipe emissions and tobacco smoke. At four of the six study sites, pedestrian volume was higher on days and times when $PM_{2.5}$ concentrations were comparatively low. Implications for policy and planning are discussed.

1. Introduction

Renewed interest in 'traditional' urban land use patterns and designs, such as moderate density mixed-use development, multi-modal transit networks, and pedestrian friendly streetscapes with wide sidewalks and short, well-connected city blocks, has coincided with an expanding body of literature suggesting that pedestrian-oriented designs may offer numerous benefits, including the positive health outcomes associated with walking and cycling to work and other daily destinations (Frank, Engelke, & Schmid, 2003; Heath et al., 2006; Sallis et al., 2009). Compact, mixed-use, pedestrian-oriented developments, however, also have the potential to increase exposure to outdoor air pollution by focusing pedestrian activity within transport microenvironments that may trap and concentrate automotive emissions (de Nazelle, Rodriguez, & Crawford-Brown, 2009; Marshall, Brauer, & Frank, 2009). As de Nazelle et al. (2009, p. 406) observed, "air pollution exposure is not only a matter of the concentration field, but also where and how individuals may inhale the pollutant." There is thus a need to understand not only how different urban environments affect ambient air pollution, but also how human activity and travel patterns *interact* with the physical elements of the urban environment to shape pedestrian exposure (Boarnet et al., 2011).

Over the past decade, a substantial and growing body of research has investigated the factors affecting pedestrian exposure to air pollution within urban transport microenvironments. Airborne pollutants studied have generally included those emitted or resuspended by motor vehicles, including particulate matter (PM), black carbon (BC), carbon dioxide (CO), and nitrogen oxides (NO_X). The spatial scope of these examinations has primarily been limited to single urban districts or transportation routes (e.g., Apte et al., 2011; Greaves, Issarayangyun, & Liu, 2008; Kaur, Nieuwenhuijsen, & Colvile, 2005; Kaur et al., 2006; McNabola, Broderick, & Gill, 2008). Recently, however, researchers have begun to investigate near-roadway air pollution across multiple locations to assess the effect of site-specific characteristics such as building height, building set-backs, roadway configuration, and sidewalk design. Buonanno, Fuoco and Stabile (2011), for example, compared particulate matter concentrations among four street corridors in Cassino, Italy. Particle concentrations varied significantly between sites, owing primarily to the interaction of street geometry and wind direction. While buildings across the four sites were of similar height (∼3–5 stories),

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http://dx.doi.org/10.1016/j.scs.2014.12.001

the street corridors varied in width and traffic density. The authors concluded that wider streets (and street canyons) that are oriented in the direction of the prevailing wind will likely exhibit lower particulate counts owing to enhanced dispersion. Furthermore, a clear distance decay effect was detected, with particulate concentrations significantly higher curbside than along the building façade.

Using multiple linear regression, Boarnet et al. (2011) assessed the relationships between the concentration of fine particulate matter ($PM_{2.5}$) along sidewalks and attributes of the built environment including traffic flow, proximity to a major intersection, number of roadway lanes, and degree of street canyon (a combination of building height and continuity) among five sites in the Greater Los Angeles area. The five sites ranged from a low density (~1–2 stories), primarily residential, neighborhood in Anaheim, to high-density (>20 stories) downtown Los Angeles. Though often statistically significant, the number of roadway lanes and degree of street canyon each only accounted for less than 1% of the variation in $PM_{2.5}$ concentrations. Proximity to a major intersection was not significant, while results of traffic flow were mixed with number of cars positively associated with, and number of heavy duty trucks negatively associated with, $PM_{2.5}$ concentrations. Day of the week and time day alone accounted for 55% of the variation. The authors conclude that future work in this area "should account for human activity and travel patterns since the amount of time spent and the level or physical activity in transportation microenvironments could substantially alter personal exposure."

The aim of the present study is to contribute to the on-going effort to understand the relationships between the built environment, site-specific activity patterns, and pedestrian exposure to air pollution by (1) identifying specific contributors to average and short-duration peak $PM_{2.5}$ concentrations in mixed-use urban environments with varying typologies and design elements using a concomitant mobile air quality-video sampling system, and (2) determining the degree to which pedestrian activity along sidewalks within these environments align with $PM_{2.5}$ concentrations at four separate times of day (morning, noon, afternoon, and evening), and on weekdays versus Saturdays. The goal is to characterize differences in the relative potential for personal exposure across multiple sites and built typologies, and to evaluate how different design elements and human activity come together in mixed-use urban environments to affect pedestrian exposure to fine particulates known to contribute to a range of respiratory and cardiovascular impairments (Neuberger et al., 2004; Pope et al., 2006). Given that pedestrian-oriented, mixed-use developments constitute an increasingly popular component of urban redevelopment strategies in the United States, even minor adjustments in the design and use of these environments may have substantial impacts on personal exposure to near-roadway ambient air pollution.

2. Methods

2.1. Study area and sites

Pedestrian exposure to $PM_{2.5}$ was evaluated for six sites within Omaha, Nebraska (Fig. 1). With an estimated population of 895,151 in 2013 (U.S. Census Bureau, 2013), the Omaha-Council Bluffs metropolitan area (i.e., 'Greater Omaha') is the most populous urban area in Nebraska and the 60th most populous metropolitan area in the United States. Five of the six sites were chosen to represent a spectrum of development patterns ranging from low-density, horizontal mixed-use to moderate density, vertical mixed use. Exhibiting low-density segregated land use typical of many suburban areas in the United States, the Dodge/72nd Street site was included in the analysis primarily as a control against which the five mixed-use sites could be compared. Based on proximity to common daily destinations such as schools, restaurants, grocery stores, and parks, each of the five mixed-use sites exhibited a 'very walkable' environment (Walk Score, 2014).

The six study sites included:

Dodge/72nd Street: High-volume six-lane suburban arterial street corridor flanked by low-density commercial development with ample setbacks and off-street parking only. Sidewalks approximately a meter wide on either side of the street are situated between .5 and 2 m from the roadway.
Benson: Popular entertainment district with a traditional 'main street' morphology. Sidewalks approximately 2 m wide abut a mix of one- and two-story commercial/retail buildings. The two-way street includes a center turning lane and space on either side for parallel parking. The parallel parking spaces separate narrow sidewalks from the roadway.
Old Market: Located less than a kilometer southeast of the city's central business district (CBD), the site consists of two- to six-story repurposed 19th century warehouses that today house retail and entertainment on the ground floor with offices and housing above. Sidewalks are 4–5 m wide, on average, among much of the route. The two-lane roadway is surfaced with cobblestones that act to reduce traffic speed. Head-in parking is available on either side the roadway.
Midtown Crossing: New and extensive (approximately 9.3 ha of floor space) mixed-use development with retail on the first floor, and up-scale apartments and condos extending up four to six additional stories. The roadway, comprised of three lanes (two lanes uphill and west-bound, one lane downhill and east-bound), is joined with head-in angled parking and sidewalks an average of 2.5–3.5 m wide on either side. A separated, two-tier sidewalk system is present along part of the walking route.
Downtown A: Along with Downtown B, located in the heart of downtown Omaha's CBD. A four lane one-way street serves as a primary in-bound corridor for commuter traffic. Parallel parking is found along either side of the roadway for much of the walking route. Office buildings and high-rise condominiums provide a mid-to-high street canyon averaging 10 stories. Sidewalks are 5 m wide on average.
Downtown B: Situated one block south of Downtown A, the street handles out-bound traffic, transitioning from two lanes with head-in parking to three lanes with parallel parking. The ground-floor retail options are more varied with a number of retail shops and street cafés. Average street canyon height is 7 stories, while the width of the sidewalks is comparable to Downtown A.

2.2. Data collection

At each of the six sites, $PM_{2.5}$ and video data were collected simultaneously by pushing a custom-built data cart along the center of the sidewalk a distance of approximately 2 km four times each day (morning between 8:00 and 9:00, noon between 12:00 and 13:00, afternoon between 16:30 and 17:30, and evening between 19:30 and 20:30), once on a weekday (Monday through Thursday) and once on Saturday between June and August 2013. Each outing involved pushing the data cart at regular walking speed (~5 km/h) back-and-forth 500 m along the north sidewalk (1 km total), crossing the street near the beginning of the route, then again walking back-and-forth (1 km total) along the south sidewalk, for a total of 2 km. Total time to complete each route varied from approximately 20–30 min. In all, 48 outings (6 sites × 4 times a day × 2 days) involved walking 96 km, and yielded about 20 h of video and air quality data.

The data collection cart featured a 0.25 m^2 steel metal base, a vertical aluminum pole with handle approximately 1.8 m high, and an additional metal platform suspended at 1.5 m. The optical

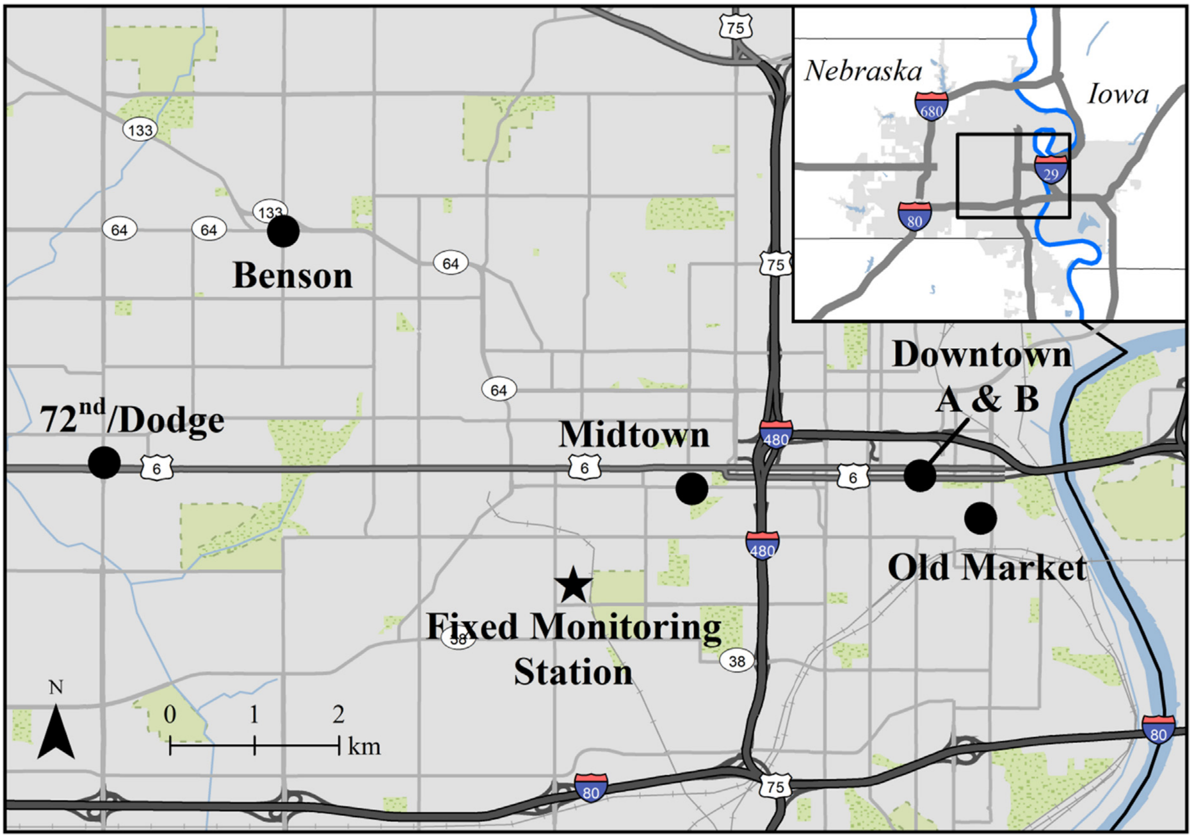

Fig. 1. Location of the six study sites and fixed monitoring station (FMS) in Omaha, NE.

particle sizer (detailed below) used to measure $PM_{2.5}$ was mounted on this second platform to approximate the height at which the average pedestrian inhales airborne pollutants. A GoPro® HD Hero3 action camera with an ultra-wide angle (170°) lens and waterproof housing was used to record HD video at 30 frames per second. The camera was attached to a monopod and secured to the left side of the data cart at a height of 2 m. Facing forward, the camera recorded video in the direction of the data cart's motion.

Fine particulate concentrations were measured at 1-s intervals using the optical particle sizer (OPS) 3330 manufactured by TSI®. The device is capable of detecting fine particulates between 0.3 and 10 μm in diameter, and sorting them in up to 16 size channels. The OPS 3330 was chosen for use in this study on the basis of its portability (2.1 kg with battery), user-friendly interface and quick response time, ability to detect a wide range of fine particle concentrations (0–3000 particles cm^{-3}) at a 1-s resolution, up to 20 h of battery life, and a combination of precision, durability, and affordability that compares well with other portable instruments commonly used in outdoor environmental monitoring (e.g., TSI P-Trak™ and DustTrak™) (Binnig, Meyer, & Kaspter, 2007; TSI®, 2012).

$PM_{2.5}$ was estimated by summing the concentration of particles sorted into the OPS' ten smallest size channels, which were custom programmed to range from 0.3 to 2.5 μm. Because the OPS 3330 is limited in its ability to detect the finest of particles within the $PM_{2.5}$ range, the device may underestimate total $PM_{2.5}$. However, the DustTrak™ Model 8520, a similar continuous-sampling optical particle counter capable of detecting particles with an aerodynamic diameter ≥0.1 μm and utilized by Boarnet et al. (2011), was found to *overestimate* particulate concentrations by as much as three times (Chung et al., 2001). Though each device has its strengths and limitations, mobile continuous-sampling devices in general may be best suited to comparing particulate concentrations across sites in relative rather than absolute terms.

The initial mass calibration of the OPS was carried out by the manufacturer (TSI) using traceable uniform Polystyrene Latex (PSL) spheres. Two on-site tests (one at Dodge/72nd, one at Downtown B) of particle density indicated good agreement (±10%) between the OPS optical measurements and its 37 mm internal filter within the 0.3–2.5 μm range. Rubber tubes 0.3 m long were attached to both the inlet and exhaust ports of the OPS and secured to opposite sides of the data collection cart to assure proper ventilation (the inlet tube faced the roadway). Video and $PM_{2.5}$ data were synchronized by carefully initiating both instruments simultaneously, with a ±2 second margin of error (sufficiently accurate to identify sources of peak concentrations).

Because meteorology can significantly influence fine particulate concentrations in urban microenvironments, temperature and humidity were continuously measured alongside particulate counts by the OPS instrument. Wind speed and direction were assessed in an open area outside, but in close proximity to, the street corridor (e.g., a nearby park, large parking lot, public plaza) using a Kestrel 4500 Pocket Weather Tracker. Taken both before and after the completion of a single walking route, the two wind speed/direction readings were then averaged for each outing. Across all six sites and 48 outings, average wind speed ranged from 0.36 to 6.11 m s^{-1} ($\bar{x} = 2$ m s^{-1}), average temperature from 18 °C to 33 °C ($\bar{x} = 26$ °C), and relative humidity from 43% to 95% ($\bar{x} = 62\%$). Average meteorological conditions observed during sampling were well within the normal range for Omaha. To control for background concentrations, $PM_{2.5}$ data (1 h resolution) collected by a fixed monitoring station (FMS) located within 6 km of all six data collection sites (Fig. 1) were obtained through the U.S. Environmental Protection Agency's (EPA) AirData database (http://www.epa.gov/airdata/).

2.3. Data processing and modeling

Particulate data were downloaded from the OPS and imported into a spreadsheet for analysis. An analysis of variance (ANOVA) was used to determine whether average $PM_{2.5}$ concentrations varied by time of day and day of the week at each of the six study sites. Weekday and weekend concentrations were compared after accounting for average daily background concentrations. Video was examined to identify sources of peak exposures and to count vehicles, pedestrians, and classify pedestrian activity (i.e., walking, biking, jogging, stationary) and vehicle type (i.e., car, bus, truck). Pedestrian and vehicles were counted only if having crossed from one side of the camera's field of view to the other. This occurred both due to the motion of the pedestrians/vehicles and the motion of the mobile data cart. To ensure counting accuracy, all video was scored by at least two individuals then averaged.

A correlation and linear regression analysis were performed to explore the potential effects of the built environment, meteorology, and human activity on pedestrian exposure to fine particulates in different mixed-use urban environments. Prior to modeling, four potential independent variables including pedestrians min^{-1}, passenger vehicles min^{-1}, buses and trucks min^{-1}, and wind speed were log-transformed to improve the normality of the datasets (i.e., all four variables exhibited significant positive skewness prior to transformation). It was also necessary to first create dummy variables for each of five categorical variables: time of day (morning, noon, afternoon, evening), day of the week (weekday, Saturday), wind direction (wind vector at an angle of 45° or less relative to the street corridor), average height of the street canyon (<5 stories or ≥5 stories; similar to Boarnet et al. (2011)), and average distance from the mid-point of the sidewalk to the roadway (<5 m or ≥5 m).

3. Results and discussion

3.1. Sidewalk $PM_{2.5}$: average concentrations

Across the six study sites, average ambient $PM_{2.5}$ concentrations ranged from 0.9 $\mu g\,m^{-3}$ on Saturday at noon and afternoon in Midtown to 16.6 $\mu g\,m^{-3}$ on a weekday morning in Midtown and a Saturday evening in Benson (Appendix A). There were, however, brief peak concentrations (averaged over one second) as high as 360 $\mu g\,m^{-3}$. For comparison, the EPA requires that average ambient $PM_{2.5}$ concentrations be no higher than 35 $\mu g\,m^{-3}$ over 24-h and no more than 12 $\mu g\,m^{-3}$ over one year to ensure public health and welfare (U.S. EPA, 2012). Fig. 2 displays $PM_{2.5}$ concentrations for four of the six study sites during select outings to highlight common patterns and exceptions. A ten-second moving average was used to improve readability (samples were taken every one second). The color-coded horizontal lines and the numbers to the right of each graph in Fig. 2 indicate the average concentration for that outing; the capital letters beside them indicate whether the averages are significantly different (different letters indicate significant difference at $p < 0.05$). At the Dodge/72nd site, for example, average $PM_{2.5}$ concentrations differed significantly across all four times of day, with the highest average concentration observed in the morning (11.8 $\mu g\,m^{-3}$), followed by afternoon (9.6 $\mu g\,m^{-3}$), noon (7.6 $\mu g\,m^{-3}$), and evening (6.8 $\mu g\,m^{-3}$) (Fig. 2A). The black lines indicate the daily average "background" concentration observed at the nearest FMS. Overall, daily average sidewalk concentrations were similar to background levels, with ambient concentrations averaged for each outing highly correlated ($r^2 = 0.748$, $p < 0.05$; Table 1) with hourly measurements taken at the FMS.

Concentrations of particulate matter often peak in the mornings and on weekdays due to enhanced traffic flow and conducive atmospheric conditions such as lower humidity and restricted mixing depths during the morning hours (Hueglin et al., 2005; Wang & Christopher, 2003). Though $PM_{2.5}$ concentrations observed at most sites and days conformed to these expectations (e.g., Dodge/72nd on a weekday; Fig. 2A) there were two notable exceptions: Benson on a Saturday (Fig. 2B), and Downtown B on a weekday (Fig. 2C). As a popular entertainment destination with an eclectic mix of bars, restaurants, music venues, and coffee shops, pedestrian traffic in Benson peaked later in the day and on Saturday (Appendix A). On Saturday in Benson, sidewalk $PM_{2.5}$ was also significantly higher in the evening than at other times of day; however, the average evening concentration was only 0.6 $\mu g\,m^{-3}$ higher than at the FMS 5 km away (Appendix A). At site Downtown B, by contrast, $PM_{2.5}$ recorded during the noon outing on a weekday was not only significantly higher than at other times of day, it was also 7.3 $\mu g\,m^{-3}$ (68%) higher than at the FMS (Fig. 2C; Appendix A). Downtown B's 2–3 lane one-way street serves as one of downtown Omaha's primary out-bound corridors, particularly during weekdays. Similarly, Downtown A serves as an in-bound corridor and, as anticipated, exhibited the highest concentrations in the morning and at noon on weekdays when commuters are entering downtown (Fig. 2D). Thus, although conditions are typically conducive to the enhancement of airborne $PM_{2.5}$ within the near-roadway environment during the morning hours, there exists some variability by location that depends on site-specific hourly and daily activity patterns.

3.2. Identifying factors associated with sidewalk $PM_{2.5}$ averages

The example presented above of Benson on Saturday evening is indicative of the strong association between $PM_{2.5}$ at the six study sites and at the FMS. Although Boarnet et al. (2011) found that the majority (55%) of the variability in sidewalk $PM_{2.5}$ concentrations at five locations in Los Angeles were attributable to day and time of day, background FMS values also accounted for 6%, while built environment variables together accounted for one percent of the variability. To assess the potential role of these factors in influencing ambient sidewalk concentrations in the present study, a regression analysis was performed in which each of the 48 outings represent an individual data point, with all variables aggregated at this level. A preliminary correlation analysis revealed that two potential independent variables, background $PM_{2.5}$ measured at a nearby FMS and relative humidity, were significantly ($p < 0.05$) correlated with ambient sidewalk $PM_{2.5}$ (Table 1). The two variables were therefore selected for inclusion in the regression analysis (discussed below) along with the categorical variables time of day, day of the week, wind direction, average height of the street canyon, and average distance from the mid-point of the sidewalk to the roadway.

Table 2 presents the results of the modeling procedure. Three alternative regression models were produced using combinations of three significant independent variables: hourly $PM_{2.5}$ averages at the FMS, relative humidity, and Saturday (the day of the week dummy variable). As indicated by the model's r^2, background $PM_{2.5}$ concentration recorded at the FMS accounted for 56% of the variation in ambient sidewalk $PM_{2.5}$. Contributing to modest increases in r^2, relative humidity accounted for an additional 8% of the variability, and Saturday (vs. weekday) 4%. While the time of day dummy variable did not prove significant in the regressions, it is important to consider that atmospheric conditions such as relative humidity and temperature often vary significantly by time of day. In fact, over the course of the 48 outings, relative humidity was significantly higher, and temperature significantly lower, in the morning relative to noon, afternoon, and evening.

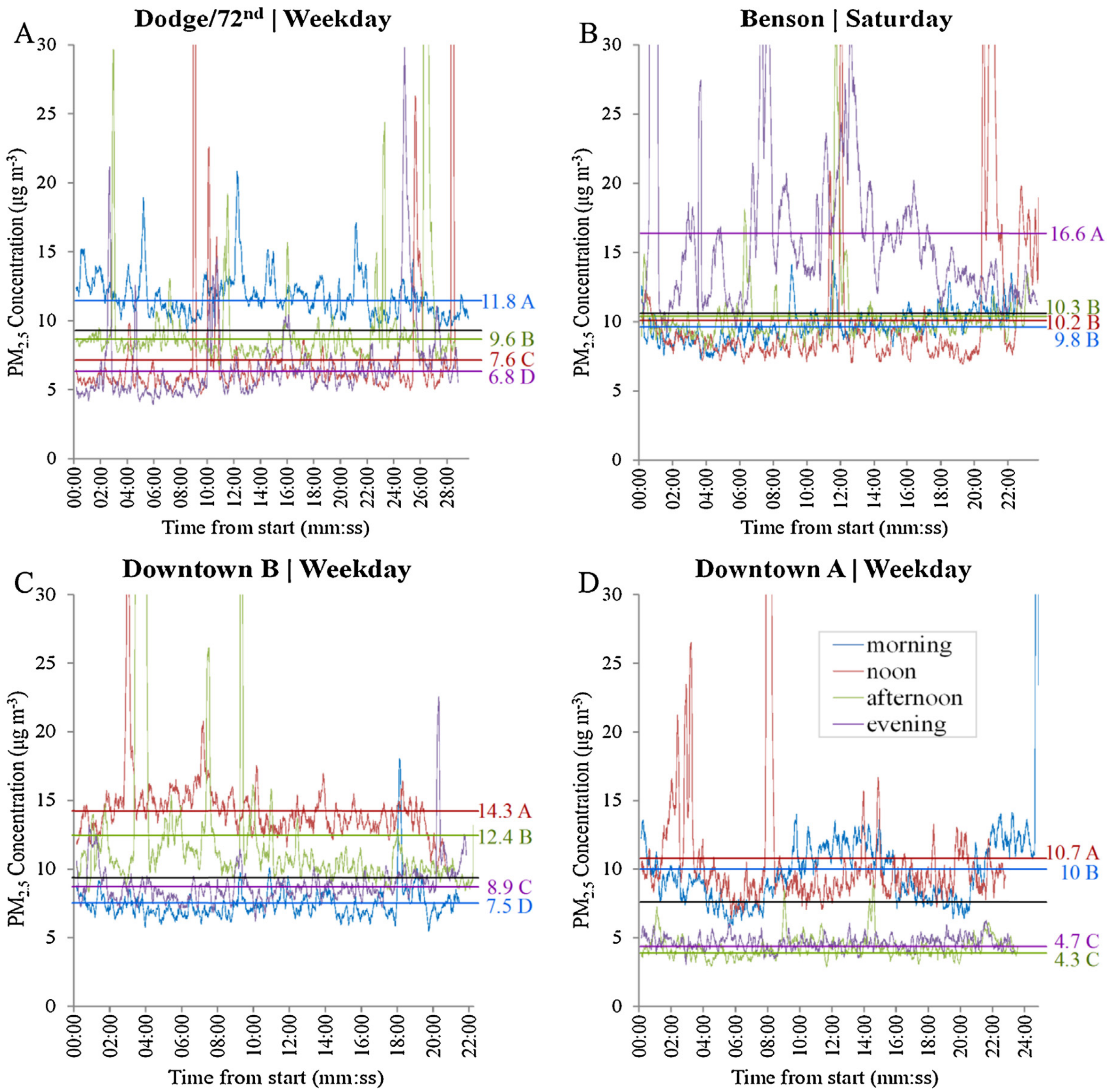

Fig. 2. Sidewalk $PM_{2.5}$ concentrations (10-s averages) for select study sites and outings. The vertical axes are constrained to 30 $\mu g\,m^{-3}$ to allow visualization and comparison of non-peak concentrations. Colored horizontal bars indicate average sidewalk $PM_{2.5}$ concentrations at each of four times of day (morning, noon, afternoon, evening). Different letters (A–D) to the right indicate significantly different average sidewalk $PM_{2.5}$ concentrations. Black horizontal lines indicate daily $PM_{2.5}$ averages recorded at the FMS.

Table 1
Correlations between $PM_{2.5}$ along the sidewalk, $PM_{2.5}$ at the FMS, and site characteristics.

	Sidewalk $PM_{2.5}$	FMS $PM_{2.5}$	Log(Pedestrians, min^{-1})	Log(Passenger vehicles, min^{-1})	Log(Buses & Trucks, min^{-1})	Temperature (°C)	Log(Wind speed ($m\,s^{-1}$))
FMS $PM_{2.5}$	**0.748****	1					
Log(Pedestrians, min^{-1})	−0.029	0.076	1				
Log(Passenger vehicles, min^{-1})	−0.108	−0.041	**−0.425****	1			
Log(Buses & Trucks, min^{-1})	0.086	−0.164	**−0.295***	**0.470****	1		
Temperature (°C)	0.238	**0.440****	0.003	**0.287***	−0.098	1	
Log(Wind speed ($m\,s^{-1}$))	−0.174	0.027	−0.004	−0.271	**−0.375****	0.063	1
Relative humidity	**0.375****	0.130	**−0.292***	−0.056	**0.371****	**−0.506****	**−0.326***

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 2
Results of the linear regression analysis.

Model	Variable	Model r^2	b	SE b	β	p-value
1	Constant	0.559	2.172	1.020		0.039
	FMS $PM_{2.5}$		0.689	0.090	0.748	0.000
2	Constant	0.637	−3.359	2.005		0.101
	FMS $PM_{2.5}$		0.655	0.083	0.711	0.000
	Relative humidity		0.095	0.030	0.282	0.003
3	Constant	0.669	−1.900	2.06		0.361
	FMS $PM_{2.5}$		0.650	0.081	0.705	0.000
	Relative humidity		0.085	0.030	0.252	0.007
	Saturday		−1.532	0.740	−0.182	0.044

The results of the regression analysis highlight the need to control for regional background concentrations when comparing ambient $PM_{2.5}$ between sites. The higher predictive power of background concentrations observed in this study relative to Boarnet et al. (2011) may be due in part to aggregating variables at the time scale of individual outings rather than every 1 min. However, both the study area and the encompassing urban area in Omaha is appreciably smaller in areal extent than those examined by Boarnet et al. (2011) in Los Angeles, potentially resulting in more uniform values across study sites, and between study sites and the FMS.

Although the results of the correlation and regression analyses confirm the importance of time- and day-specific atmospheric conditions, and the strong association between $PM_{2.5}$ concentrations observed along the sidewalk and at a FMS, the impact of site-specific conditions on personal exposure should not be discounted. Site-specific activity patterns that vary between weekdays and weekends, and by time of day, not only have the potential to impact variations in average $PM_{2.5}$ concentrations; they may also affect the nature and magnitude of short-duration peak concentrations, as well as the overall exposure risk to pedestrians.

3.3. Sidewalk $PM_{2.5}$: peak concentrations

Fig. 3 displays the complete range of sidewalk $PM_{2.5}$ concentrations for select study sites. Peak concentrations of $PM_{2.5}$ briefly exceeded 50 $\mu g\,m^{-3}$ (using 1-s averages) over thirty separate times during the course of the study. The highest single peaks in concentration were recorded around noon on a weekday at Dodge/72nd (Fig. 3A), where two busy six-lane suburban arterials intersect. Here, peak concentrations exceeded 300 $\mu g\,m^{-3}$ twice: once when passing a pickup truck parked less than 2 m from the sidewalk, and again when a motorcycle passed traveling uphill in the lane nearest the sidewalk. In general, brief spikes in ambient $PM_{2.5}$ were due mainly to either vehicle tailpipe emissions or tobacco smoke.

Individual study sites experienced unique patterns of peak concentrations that varied by time of day and between weekdays and Saturdays. For example, the popular entertainment districts Benson and the Old Market stand out as the only two sites where spikes in $PM_{2.5}$ were recorded on Saturdays as well as weekdays. At both locations, and for each of the four times of day, more pedestrians were observed on Saturday than on a weekday (Appendix A). The effect of this additional pedestrian volume was noticeable in the Old Market on Saturday when the mobile data cart came in close proximity to a number of pedestrians using tobacco products (Fig. 3B). These interactions occurred primarily during the morning and evening outings. Pedestrian volume in the Old Market on Saturday morning was higher than may be expected due to a nearby Farmer's Market. Differences in peak concentrations by time of day were particularly striking between weekday and Saturday in Benson (Fig. 3C and D). On a weekday, peak concentrations were observed at all times of day except evening. On Saturday, however, spikes in $PM_{2.5}$ occurred most frequently in the evening. Notably, the source of at least three peak concentration events in Benson were due to idling passenger vehicles parallel parked immediately adjacent to the sidewalk. Further examination of the video recordings revealed that in each case the vehicle's tailpipe was directed toward the sidewalk. Given the wider and more sheltered sidewalks of the Old Market, it is perhaps not unexpected that most peak concentrations identified there were associated with tobacco smoke rather than vehicle tailpipe emissions.

Peak concentrations above 50 $\mu g\,m^{-3}$ were noticeably absent at Dodge/72nd, Downtown A, and Downtown B on Saturday, and at Midtown on both Saturday and a weekday. Part of this variation was due to random chance; however, the data suggest that the probability of encountering peak concentrations of 50 $\mu g\,m^{-3}$ or higher along the sidewalk on a Saturday versus a weekday varies by location. In contrast with Benson and the Old Market, the land use at Downtown A and B consists primarily of high-rise office space and condominiums, with retail on the ground floor catering mainly to office workers during the business day (~700–1800 M–F). Total pedestrian volume and vehicular traffic were therefore markedly reduced on Saturdays when the majority of office workers and customers were absent. Among the highest density of bus/truck traffic were also observed at the two Downtown sites, which, when combined with the highest street canyons in the study, likely increased the probability of pedestrian exposure to elevated peak concentrations of $PM_{2.5}$ during the work week (Charron & Harrison, 2005; Kinney et al., 2000). Buses constituted the majority of the large vehicular traffic, with 14 recorded during a single outing at Downtown B on a weekday afternoon. Note that all identified peak concentrations above 50 $\mu g\,m^{-3}$ at Downtown B, where vehicles were traveling uphill, were attributable to city buses (Fig. 3E), while at Downtown A, where vehicles were traveling downhill and thus expending less fuel, were attributable only to smoking receptacles (Fig. 3F). Both Downtown A and B serve as major transportation corridors for the Omaha city bus system, with some 350 buses passing through Downtown B daily. The street corridor, however, is undergoing an overhaul that will reroute several bus lines through a new transit center currently in the planning phase (Golden, 2013).

Midtown was the only site in which substantially higher than average peak concentrations were not observed (Fig. 4G and H). Much of the Midtown site is comprised of a single planned unit development completed in 2010. Along much of the walking route, head-in parking and sidewalks 3–5 m wide help separate pedestrians and tailpipe emissions. Another potentially relevant design feature unique to this location is the presence, along certain sections of the route, of two parallel sidewalks; one elevated and proximate to the building, the other at street level and adjacent to the on-street parking. This configuration not only reroutes some pedestrian traffic further from the roadway, it also dissipates pedestrian density. As in the Old Market, the head-in parking found along much of the Midtown route may have also reduced peak sidewalk concentrations.

Dodge/72nd exhibited the most dramatic change in peak concentrations between weekday and Saturday. The location had the heaviest vehicular traffic volume, with up to 59 passenger

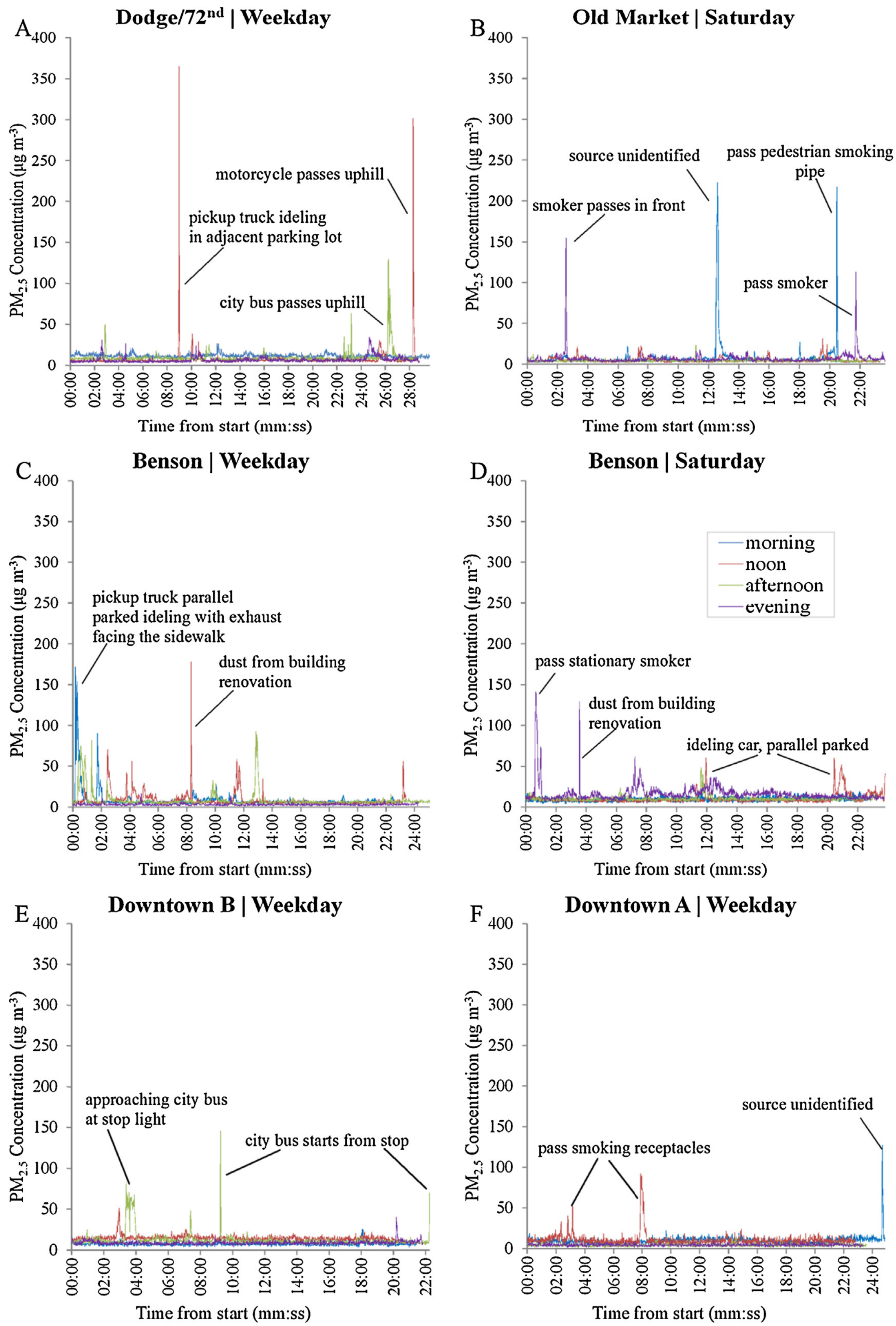

Fig. 3. The full range of sidewalk $PM_{2.5}$ concentrations (1-s averages) for select study sites and outings show significant short-duration peaks with often identifiable sources.

vehicles min^{-1} and nearly one bus or truck every minute on a weekday. With the exception of passenger vehicle traffic on Saturday evening, total traffic volume decreased substantially on Saturday, reflecting a decrease in commuting trips as well as commercial trucking activity. Flanked by one-story buildings with substantial set-backs, $PM_{2.5}$ and other air pollutants are likely to disperse more easily at Dodge/72nd than at the other five study sites. Pedestrians, if not immediately proximate to the source of $PM_{2.5}$

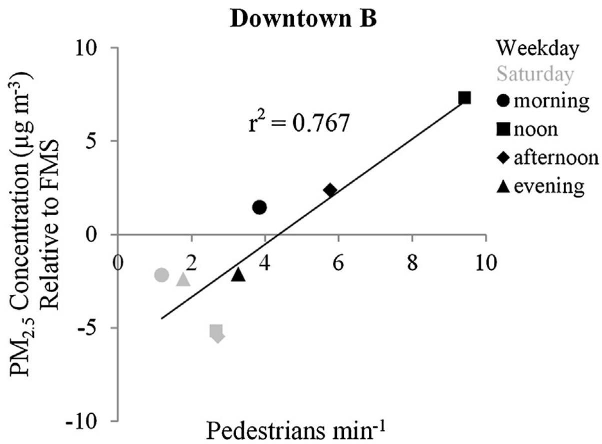

Fig. 4. A significant ($p < 0.05$) correlation between sidewalk $PM_{2.5}$ concentrations relative to background (FMS) and pedestrians min^{-1} was observed at Downtown B, indicating the potential for higher exposures.

(as demonstrated during the weekday outing), are likely to benefit from the enhanced air flow at the site. While the four Saturday outings at Dodge/72nd may represent anomalously consistent sidewalk concentrations, it is also probable that fewer buses, trucks, and passenger vehicles on the roadway on Saturday contributed to fewer observed spikes in $PM_{2.5}$. As the only study site not representative of either traditional or neo-traditional mixed-use development, the patterns in sidewalk $PM_{2.5}$ at Dodge/72nd are also instructive as a means of comparison. Similar to the other five sites, average concentrations at Dodge/72nd were generally comparable to background levels, while peak concentrations were moderately higher, though no more frequent. Given the corridor's sparse pedestrian activity and often superior ventilation, however, relatively few spikes in peak concentrations may be expected from cigarette and cigar smoke provided that the pedestrian is in motion rather than situated at a bus stop, etc.

3.4. Assessing total exposure: concentrations vs. pedestrian volume

While activity patterns and particulate air pollution have often been studied independently to assess the impacts of the built environment on human health, it is also useful to consider them together to examine how their interaction may affect personal exposure. Keeping in mind the limited sample size (eight data points gathered during eight outings at each site), a noticeable, though non-significant, negative trend was observed at Dodge/72nd and Benson in which fewer pedestrians were observed on days and times with the highest sidewalk $PM_{2.5}$ concentrations relative to the FMS. The Old Market, Midtown, and Downtown A exhibited essentially negligible trends in relative concentrations versus pedestrian volume. Data collected at Downtown B, however, suggests a strong positive and statistically significant ($r^2 = 0.767$, $p = 0.03$) correlation between relative concentrations and pedestrians (Fig. 4). Both pedestrian volume and relative $PM_{2.5}$ concentrations along the sidewalk were particularly high at noon on a weekday when office workers took to the sidewalks for lunch. Average concentrations and pedestrian volume at Downtown B remained elevated in the afternoon as well, reflecting the day's second peak commute time. This is not to suggest a causal relationship between pedestrian volume and sidewalk $PM_{2.5}$; only that more pedestrians within the downtown corridors (particularly Downtown B) were outside on days and at times (i.e., around noon and evening during the work week) when ambient $PM_{2.5}$ concentrations compared to the FMS were relatively high.

With the possible exception of Downtown B, there is little evidence from these data that pedestrians in moderate-density, mixed-use developments will be exposed to substantially higher average concentrations of $PM_{2.5}$ relative to suburban strip-mall environments such as Dodge/72nd Street, or within a primarily residential area like the one encompassing the FMS. Although the Old Market boasted the highest pedestrian counts of any site, average sidewalk $PM_{2.5}$ concentrations there were lower than those detected at the FMS on seven of eight outings. The relatively low traffic volume in the area, combined with wide sidewalks and head-in parking appear to have provided a relatively sheltered environment for pedestrians, although peak exposures due to tobacco smoke remains a concern. The situation at Downtown A and B, with more pedestrians on the sidewalk at times of elevated $PM_{2.5}$, may benefit from site design modifications discussed in the next section.

3.5. Implications for policy and planning

Compact, pedestrian-oriented and mixed-use urban forms have the potential to both increase personal exposure to air pollution by bringing more people into contact with elevated concentrations, and decrease exposures by reducing the emissions associated with fossil-fuel dependent vehicles. At the regional level, movement toward a more compact urban form is expected to result in fewer emissions and improved air quality (Bereitschaft & Debbage, 2013; Borrego et al., 2006). At the neighborhood-scale, however, the evidence is mixed, with computer models indicating a negligible overall change in pedestrian exposure with enhanced neighborhood walkability (de Nazelle et al., 2009), while studies involving on-site mobile measurements of $PM_{2.5}$ have generally indicated that concentrations in compact neighborhoods are higher than at background locations (Boarnet et al., 2011; Charron & Harrison, 2005; Kaur et al., 2005). These data, however, were collected in cities substantially larger than Omaha with higher traffic volumes both at the local and regional scale. In the present study, although variations in average and peak $PM_{2.5}$ concentrations were observed between some sites (as well as by time and day), average concentrations were frequently comparable to background FMS values. Thus, when taking into account the additional positive health outcomes associated with denser, pedestrian-oriented environments, such as greater physical activity, lower body mass indices, and lower rates of obesity and type-2 diabetes (Lovasi, Neckerman, Quinn, Weiss, & Rundle, 2009; Müller-Riemenschneider et al., 2013; Saelens, Sallis, Black, & Chen, 2003), the balance appears to tip in favor of compact, rather than dispersed, development.

Not all compact designs are equally advantageous, however. The results of this investigation suggest that pedestrian exposure to both peak and average concentrations of $PM_{2.5}$ could be reduced by modifying the built environment as well as reducing *in situ* emissions. As mentioned in Section 3.3, a cross-street (16th Street) to both Downtown A and B is undergoing renovations as of summer 2014 (one year following data collection). The re-routing of bus traffic away from these corridors will likely reduce pedestrian exposure to $PM_{2.5}$, but may also inconvenience bus passengers who work within close proximity of existing bus stops. A more equitable solution would be to phase out the current diesel-powered buses in favor of electric–gasoline hybrids or buses fueled with natural gas. Several cities have begun testing cleaner fully-electric and hydrogen fuel cell-powered buses, which are substantially more expensive up-front, but increasingly cost-competitive over their life-cycle (Scott, 2013; U.S. DOT, 2012; Zimora et al., 2011). The streetscape renovation project will also entail narrowing the sidewalk along 16th street and adding 95 parallel and back-in parking spaces, which will likely increase pedestrian exposure to $PM_{2.5}$ and other tailpipe emissions. At both the Benson and Dodge/72nd sites, vehicles idling with tailpipes directed toward the sidewalk resulted in several peak exposures exceeding 50 μg m^{-3}. Spikes in $PM_{2.5}$ at sites with only head-in parking (i.e., the Old Market, Downtown B), by contrast, were due to either large vehicles in the roadway or fellow pedestrians. Head-in parking may therefore be the best option to minimize exposure, though commentators have argued in favor of either method of parking, citing various safety advantages (Meltzer, 2013). The efficacy of different parking methods is in need of further study.

By smoking tobacco products on or adjacent to the sidewalk, pedestrians and customers of open-air bars and restaurants contributed significantly at times to elevated concentrations of $PM_{2.5}$. Though perhaps more challenging to address than tailpipe emissions, there may be ways to mitigate personal exposure. On the structural side, Midtown's two-tier sidewalk design gives pedestrians more room to maneuver around sources of tobacco smoke. Though certainly not practical to implement everywhere, the advantages of this design should be considered where applicable. A much simpler modification involves relocating smoking receptacles to the least-trafficked areas, such as away from store entrances and behind establishments. Extending indoor smoking bans to outdoor public areas has also been gaining traction as a strategy to reduce pedestrian exposure to second-hand smoke. In January 2011, the village of Great Neck, New York became one of the first municipalities in the United States to ban smoking on public sidewalks, and a recent survey conducted in New York City suggests that the nation's largest city may soon consider a similar measure (Reiss & Rafferty, 2011; Saletan, 2012).

4. Conclusion

The results of this study suggest that mixed-use and pedestrian-oriented corridors, specifically those with moderate densities and situated within mid-sized U.S. metropolitan areas, are generally not expected to exhibit average $PM_{2.5}$ concentrations that significantly exceed those along a busy suburban corridor or at a nearby fixed monitoring station. Average sidewalk $PM_{2.5}$ concentrations, however, often varied significantly by time of day and between weekdays and Saturdays, owing primarily to differences in site-specific activity patterns. The elevated evening concentrations observed in the Old Market and Benson on Saturdays, for example, is reflective of the increase in afternoon and evening activity typical of entertainment districts. Downtown A and B likewise demonstrated that one-way in-bound and out-bound corridors can expect elevated concentrations in line with peak commute times. When comparing average $PM_{2.5}$ values across sites, much of the variability in average $PM_{2.5}$ could be explained by background concentrations, relative humidity, and day of the week (weekday vs. Saturday). Boarnet et al. (2011) demonstrated that certain elements of the built environment may contribute significantly to differences in concentrations, yet the results of their analysis, and of this study, suggest that these features accounted for relatively little of the overall variability observed in sidewalk $PM_{2.5}$. By simultaneously recording video while collecting samples of $PM_{2.5}$, specific design features that influence pedestrian flow and their interactions with one another and with vehicles, such as the width of the sidewalk, average pedestrian distance from the roadway, orientation of parking spaces (i.e., head-in vs. back-in vs. parallel), placement of smoking receptacles, and the type of fuel used by public transit, were, however, clearly implicated in the frequency and magnitude of peak $PM_{2.5}$ concentrations.

Mixed-use and pedestrian-oriented urban environments are increasingly viewed as healthier alternatives to suburban typologies by encouraging active rather than automotive transport. One potential downside, however, is enhanced pedestrian exposure to air pollution in the near-roadway environment. While the results of this study do not deny the possibility of enhanced pedestrian exposure to $PM_{2.5}$ within denser, more compact urban environments, they do suggest that such differences may be minimal in a mid-sized metropolitan area with moderates densities and traffic volumes. Additionally, a significant positive relationship between $PM_{2.5}$ (relative to background concentrations) and pedestrian volume was observed at only one site (Downtown B), while four of the six sites generally hosted more pedestrians on days and times during which concentrations were relatively low, or at least comparable to background levels. Future research could more fully compare the relative potential for personal exposure by taking into account the level of physical activity engaged in by pedestrians (e.g., walking, biking, jogging, stationary) in addition to total pedestrian traffic counts. A GPS device could also be used to track more precisely the movement of the data collection cart and provide enhanced data visualization. This information may be particularly salient when evaluating and comparing urban microenvironments known to exhibit concentrations well above background levels, or in larger cities where there is likely to be greater variability in $PM_{2.5}$ among study sites.

Appendix A. Data collected at each of the six study sites organized by day and time.

	No. Samples	Mean Sidewalk $PM_{2.5}$	SD	FMS $PM_{2.5}$	Passenger vehicles	Buses/Trucks	Walking	Stationary	Jog/Cycle	Total Pedestrians
	$PM_{2.5}$				Vehicles min^{-1}		Pedestrians min^{-1}			
Morning Week										
Dodge/72nd	1800	11.8	2.1	10	54	0.93	0.10	0.00	0.00	0.10
Benson	1350	8.7	12.7	4	6	0.04	0.44	0.18	0.04	0.67
Old Market	1330	15.9	2.2	10	2	0.14	0.86	0.41	0.05	1.31
Midtown	1255	16.6	1.9	18	14	0.24	0.86	0.96	0.10	1.91
Downtown A	1510	10.0	5.6	8	14	0.68	3.81	0.60	0.12	4.53
Downtown B	1295	7.5	2.0	6	5	0.65	2.04	1.76	0.05	3.85
Morning Saturday										
Dodge/72nd	1650	13.5	2.1	13	15	0.40	0.07	0.00	0.00	0.07
Benson	1360	9.8	2.1	7	3	0.13	0.57	0.40	0.04	1.02
Old Market	1300	7.4	16.4	11	4	0.09	4.11	0.69	0.14	4.94
Midtown	1270	3.7	2.0	5	3	0.14	0.99	0.38	0.09	1.46
Downtown A	1420	7.1	2.4	5	8	0.30	0.76	0.38	0.21	1.35
Downtown B	1215	15.8	1.9	18	5	0.10	0.69	0.30	0.20	1.19
Noon Week										
Dodge/72nd	1650	7.6	15.3	8	55	0.91	0.04	0.22	0.00	0.25
Benson	1405	8.4	8.9	8	7	0.26	1.32	0.47	0.04	1.41
Old Market	1265	14.2	2.9	18	6	0.14	8.06	2.61	0.38	11.1
Midtown	1205	16.0	1.9	18	14	0.10	4.88	1.20	0.20	6.27

	No. Samples	Mean Sidewalk $PM_{2.5}$	SD	FMS $PM_{2.5}$	Passenger vehicles	Buses/Trucks	Walking	Stationary	Jog/Cycle	Total Pedestrians
		$PM_{2.5}$			Vehicles min^{-1}		Pedestrians min^{-1}			
Downtown A	1355	10.7	7.7	10	14	0.31	7.04	1.46	0.04	8.55
Downtown B	1260	14.3	3.4	7	8	0.19	7.05	2.24	0.14	9.43
Noon Saturday										
Dodge/72nd	1670	9.9	1.9	13	38	0.22	0.14	0.07	0.00	0.22
Benson	1440	10.2	6.2	10	8	0.08	2.29	0.58	0.17	3.04
Old Market	1400	4.9	3.0	10	8	0.00	12.8	6.30	0.09	19.2
Midtown	1260	1.7	0.9	4	10	0.10	3.29	0.52	0.19	4.00
Downtown A	1455	4.4	1.3	8	16	0.21	1.28	0.41	0.12	1.81
Downtown B	1240	14.8	1.9	20	6	0.15	1.84	0.77	0.05	2.66
Afternoon Week										
Dodge/72nd	1680	9.6	7.8	9	59	0.46	0.21	0.04	0.00	0.25
Benson	1630	8.5	9.4	10	17	0.11	0.92	0.26	0.07	1.25
Old Market	1265	14.2	2.9	18	6	0.14	8.06	2.61	0.38	11.1
Midtown	1205	16.0	1.9	18	14	0.10	4.88	1.20	0.20	6.27
Downtown A	1355	10.7	7.7	10	14	0.31	7.04	1.46	0.04	8.55
Downtown B	1260	14.3	3.4	7	8	0.19	7.05	2.24	0.14	9.43
Afternoon Saturday										
Dodge/72nd	1640	7.0	1.6	11	29	0.18	0.11	0.07	0.00	0.18
Benson	1400	10.3	3.2	10	5	0.09	1.54	0.21	0.00	1.76
Old Market	1400	4.2	1.5	9	9	0.13	10.3	6.64	0.13	17.1
Midtown	1200	2.3	0.9	5	10	0.05	2.40	0.40	0.05	2.85
Downtown A	1340	4.8	1.6	6	10	0.22	1.48	0.22	0.09	1.79
Downtown B	1280	12.5	2.0	18	6	0.09	1.41	1.31	0.00	2.72
Evening Week										
Dodge/72nd	1650	6.8	3.5	9	47	0.11	0.18	0.00	0.00	0.18
Benson	1440	3.2	1.3	9	14	0.04	1.88	0.83	0.17	2.88
Old Market	1332	8.0	8.1	17	9	0.00	8.11	5.50	0.00	13.6
Midtown	1285	12.3	1.5	11	14	0.14	2.38	0.98	0.09	3.45
Downtown A	1430	4.7	1.4	6	8	0.04	0.42	0.29	0.17	0.88
Downtown B	1230	8.9	2.4	11	5	0.05	2.24	0.88	0.15	3.27
Evening Saturday										
Dodge/72nd	1600	8.1	2.2	12	54	0.15	0.53	0.04	0.00	0.56
Benson	1430	16.6	11.0	16	7	0.08	2.85	0.34	0.00	3.19
Old Market	1430	6.8	7.8	7	11	0.00	16.7	13.5	0.00	30.1
Midtown	1310	3.5	1.1	5	15	0.00	2.79	0.69	0.00	3.48
Downtown A	1400	4.5	1.5	4	8	0.00	0.64	0.13	0.04	0.81
Downtown B	1220	12.6	2.1	15	4	0.00	0.93	0.84	0.00	1.77

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