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ABSTRACT
This paper provides preliminary evidence that the placement of buildings influences the concentration of fine particulates by altering wind flow. The authors collected measurements of fine particulate concentration, wind speed, wind direction, and traffic levels around five Southern California arterials selected to represent a range of building densities. In some cases the difference in average concentrations between opposite sides of the street was on the order of 10 $\mu g/m^3$. In most cases the concentration was higher on the upwind side of the street, where the wind wakes of buildings limit the dispersion of particulates. Although this work is exploratory in nature, it reveals that fine particulate concentrations can vary even within a single city block, a scale finer than those used in current policy models. Given the trend towards infill development and densification in many places, this is an important topic that warrants further research to more fully understand the influence of the built environment on air quality.

I. INTRODUCTION

In this study, we give results that illuminate two gaps in the literature on fine particulate concentrations in urban areas. First, little is known about fine particulate concentrations along major arterial streets, as opposed to our relatively greater knowledge of particulate concentrations near freeways. We offer some of the first evidence on that topic. Second, patterns of wind transport and hence particulate concentration and dispersion may be affected by building placement. Computer simulations have shown that fine particulates may be trapped in wakes in the wind shadows of buildings (*1*), creating fine-grained differences in concentrations that may be important in higher density, infill developments of the sort that have become popular in the past decade. The goals of this research are twofold: (1) To measure particulate concentrations near major arterials in five neighborhoods chosen to represent built environments that range from low density auto-oriented development to dense urban settings, and (2) To get exploratory evidence on factors associated with differences in fine particulate concentrations at a fine level of geographic detail.

Fine particulate concentrations (in this paper, particulate matter with diameters 2.5 micrometers or less, $PM_{2.5}$) have been associated with several thousand premature deaths in California alone each year (*2*). Fine particulates concentrate near the source; past research near urban freeways has shown the highest concentrations within 100 meters of the freeway, dropping to background levels at distances of approximately 300 meters from the freeway (*3*). Most studies of fine particulates have focused on emissions from and concentrations near freeways (*3*, *4*) or along routes that are heavily trafficked by heavy duty diesel trucks (*5*). In the Los Angeles region (the context for this study), average annual daily traffic (AADT) on major arterial streets can be one-third the level of AADT on the busiest freeways. (Consider this example from 2005 Caltrans data: AADT on Beach Boulevard in Orange County near Warner is 81,000, compared to AADT between 270,000 and 311,000 for Interstate 405 in West Los Angeles, between Interstate 105 and Mulholland Boulevard.) As infill and compact development become more popular, building patterns will place humans in closer proximity to heavily trafficked arterial streets, increasing the need to understand fine particulate concentrations and how the built environment can influence particle concentration and dispersion in urban environments.

We hypothesize that the factors associated with fine particulate concentrations include: (1) meteorological conditions, especially wind direction and wind speed, (2) the built environment, (3) location within the region (location in the Los Angeles metropolitan area is strongly associated with wind conditions, due to prevailing onshore breezes, and with the built environment), and (4) traffic. Our results, while preliminary, show variation with the built environment, with the highest fine particulate concentrations in the study area that is best characterized as compact development. Beyond variation in fine particulate concentrations associated with the study areas, we find that wind direction interacts with building placement to create patterns of higher particulate concentration in building wakes. To date, our preliminary results do not give evidence of associations with particulate concentrations and traffic flow, beyond what would be explained by variations across the study areas and times of day, but we caution that our initial focus has been more descriptive and exploratory.

II. STUDY DESIGN

We chose major arterial streets (AADT > 40,000) in five study areas, with each study area representing different development patterns: (1) low density (structures are 1-2 stories), (2) low-rise (3-4 stories), (3) mid-rise (10-20 stories), (4) high-rise (> 20 stories), and (5) strip mall (large surface parking separating buildings and the arterial.) The study neighborhoods, by settlement type, are in the cities of Anaheim (low rise, Harbor Boulevard is the arterial street), Pasadena (low-rise, Colorado Boulevard), downtown Long Beach (mid-rise, Ocean Boulevard), downtown Los Angeles (high-rise, Grand Avenue), and Huntington Beach (strip mall, Beach Boulevard.) Each study area is approximately 0.25 square kilometers (500 meters by 500 meters) surrounding the selected arterial. In most areas, there are more than one major arterials of focus within the study areas; study areas were chosen for settlement patterns and we focus on the small 0.25 square kilometer areas, here denoted by the name of the city. Representative photos of building patterns in each study area are shown in Table 1. For reference, the Pasadena site is most typical of compact development.

TABLE 1 Representative Building Types in Each Study Area

	Low density settlement	**Low-rise settlement**	**Mid-rise settlement**	**High-rise settlement**	**A strip mall**
Stories	1 to 2 stories	3 to 5 stories	10 to 20 stories	>20 stories	1 to 2 stories
City	Anaheim	Pasadena	Long Beach	Los Angeles	Huntington Beach
Arterials	Harbor Blvd.	East Colorado Blvd.	East Ocean Blvd.	6th Ave.	Beach Blvd.
Typical buildings					

III. DATA COLLECTION

In each study area, field measurements were conducted on three consecutive days between June 19 and August 1, 2008. Fine particulate ($PM_{2.5}$) concentrations were measured using six stationary DustTrak (TSI, Inc.) monitors during three time periods on each observation day – the morning rush hour (7 to 9 a.m.), mid-day (11 a.m. to 1 p.m.), and the evening rush hour (4 to 6 p.m.) Traffic was videotaped using three video cameras (JVC) and later was counted and classified by watching the videotapes. Wind speed and direction were measured using a sonic anemometer located within each study area; whenever possible, the sonic anemometer was located on the roof of a parking structure or in an elevated or open area to obtain background wind speed and direction relatively independent of building structures.

In addition to the stationary measurements, at each study site the research team walked designated routes carrying DustTraks and video cameras to compare particulate concentrations along street segments. Typically two to three routes were walked per site, approximately three times per route, and each walkthrough lasted from three to 30 minutes. These walkthrough data are of particulate interest as, in some study areas, parallel DustTraks were carried simultaneously on opposite sides of the same street, allowing fine-grained comparisons of $PM_{2.5}$ concentrations in small geographic areas, in ways that can give insight into the relationship between fine particulate concentration, wind direction and speed, and the built environment.

For the walkthrough data, research team members carried a DustTrak in a backpack with a 32” aluminum tube attached to the DustTrak inlet protruding. The DustTrak data provide second-by-second measurements of particulate matter concentration. Members of the research team also recorded traffic conditions with a handheld video camera while walking the routes. Traffic counts concurrent with the DustTrak readings were obtained from the resulting video files.

For traffic counts, vehicles were classified as cars, trucks, or buses to broadly account for the different emission factors of different classes of vehicles. The car category includes light trucks and smaller vehicles. The truck category includes delivery trucks and larger vehicles. We organized the counts into street segments and intersections. The endpoints of a street segment are the cross-streets at either end, and the traffic count for that segment is the number of vehicles that passed along the adjacent street in either direction while the person walked from one endpoint to the other. (To control for differing lengths of street segments and hence differing time spent walking the route, traffic counts are converted into traffic per minute in all cases in the analysis presented here.) The traffic count for an intersection is the number of vehicles that passed through the intersection in any direction from the time the person reached the intersection to the time he or she reached the opposite side of the street. Thus, the intersection counts include traffic passing during the time spent standing at the intersection, time spent waiting to cross the intersection, and the time spent walking across the street. We obtained the time to the nearest second at each cutoff point from the video files.

For walkthrough data analysis, background wind speed and direction were obtained from the sonic anemometer, which gives readings at 0.1 second frequencies. Wind speed was averaged for the walkthrough time period, and for wind direction we focus on the median direction during the walkthrough time period.

We augmented the field data with building density measures obtained from parcel records for the three study areas in Los Angeles County. The parcel records contain the square feet of floor space in each parcel. We calculated the area of each parcel from the corresponding shapefile using ArcMap 9.2.

IV. RESULTS

Descriptive statistics for particulate concentrations are shown in Table 2 (walkthrough data only) and in Table 3 (stationary DustTrak data), organized by study area. In general, the Pasadena and Long Beach study areas have higher $PM_{2.5}$ concentrations.

TABLE 2 Walkthrough DustTrak $PM_{2.5}$ Concentration Data (In Micro-grams per Cubic Meter, $\mu g/m^3$)

City	n	Mean	Min[a]	1st Pctl.	25th Pctl.	50th Pctl.	75th Pctl.	99th Pctl.	Max
Anaheim	1,987	29.8	-7.3	14.7	26.1	28.6	30.8	46.3	1,874.1
Huntington Beach	13,262	31.4	12.0	17.0	28.0	31.8	35.0	46.8	554.9
Long Beach	8,072	36.6	12.5	15.3	19.7	45.2	49.7	60.4	304.3
Los Angeles	21,726	27.8	-8.2	18.4	24.4	27.0	29.6	50.8	1,418.3
Pasadena	13,097	53.0	26.8	44.1	49.8	52.5	55.2	68.4	1,315.8

[a]Negative DustTrak readings are rare aberrations. Of the 58,144 walkthrough DustTrak readings, five were negative values. Discarding those does not change the analysis.

TABLE 3 Stationary DustTrak $PM_{2.5}$ Concentration Data (In Micro-grams per Cubic Meter, $\mu g/m^3$)

City	n	Mean	Min[a]	1st Pctl.	25th Pctl.	50th Pctl.	75th Pctl.	99th Pctl.	Max
Anaheim	376,813	39.4	-90.6	7.7	28.6	35.2	47.3	77.6	2,032.1
Huntington Beach	385,060	41.9	-208.0	15.5	30.7	38.6	49.2	92.0	3,331.4
Long Beach	322,880	54.1	-517.9	17.5	41.5	55.0	64.4	95.9	457.5
Los Angeles	324,874	41.7	-674.6	15.3	28.0	39.8	54.2	77.1	9,585.2
Pasadena	385,280	60.4	-414.0	21.9	48.0	57.0	74.0	114.8	30,929.0

[a]Negative DustTrak readings are rare aberrations. Of the 1,794,907 stationary DustTrak readings, 656 were negative values. Discarding those does not change the analysis.

A. Differences by Side of Street

In walkthrough routes in two of the study areas, two people walked the same route in tandem, one on each side of the street. Those parallel routes are shown in Figures 1 and 2 (respectively the Huntington Beach and Pasadena study areas), with the median wind direction during each day's walkthrough shown on the figures. (There were typically one to three consecutive passes through the walkthrough route on each observation day.) Figures 1 and 2 show all walkthrough routes, which includes both parallel routes (shown as straight lines) and loop routes. Here we only focus on the straight-line routes, as those were the only routes where observers with portable DustTrak devices walked in tandem on opposite sides of the street. Those straight line routes are Huntington Beach Routes A (Garfield Avenue) and B (Beach Boulevard) and Pasadena Route B (Colorado Boulevard.).

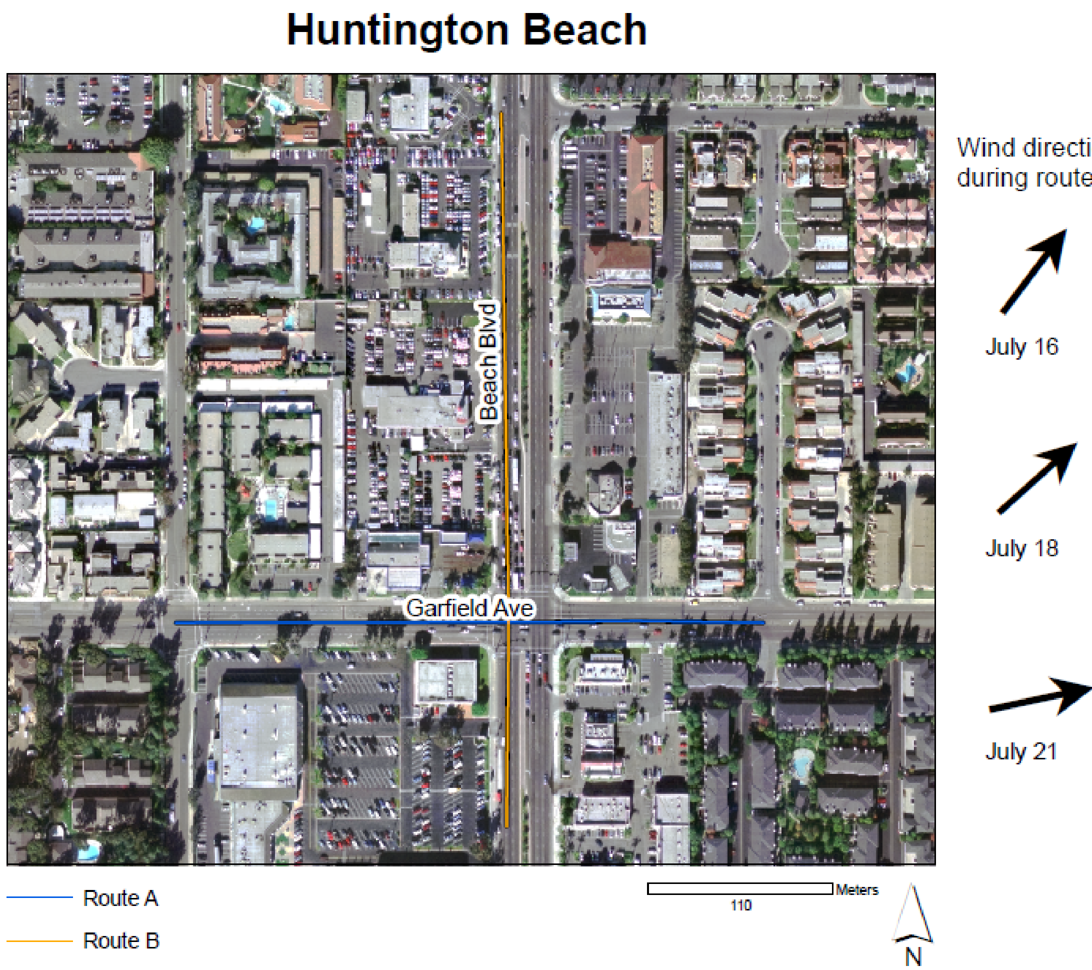

FIGURE 1 Huntington Beach study area and walkthrough routes.

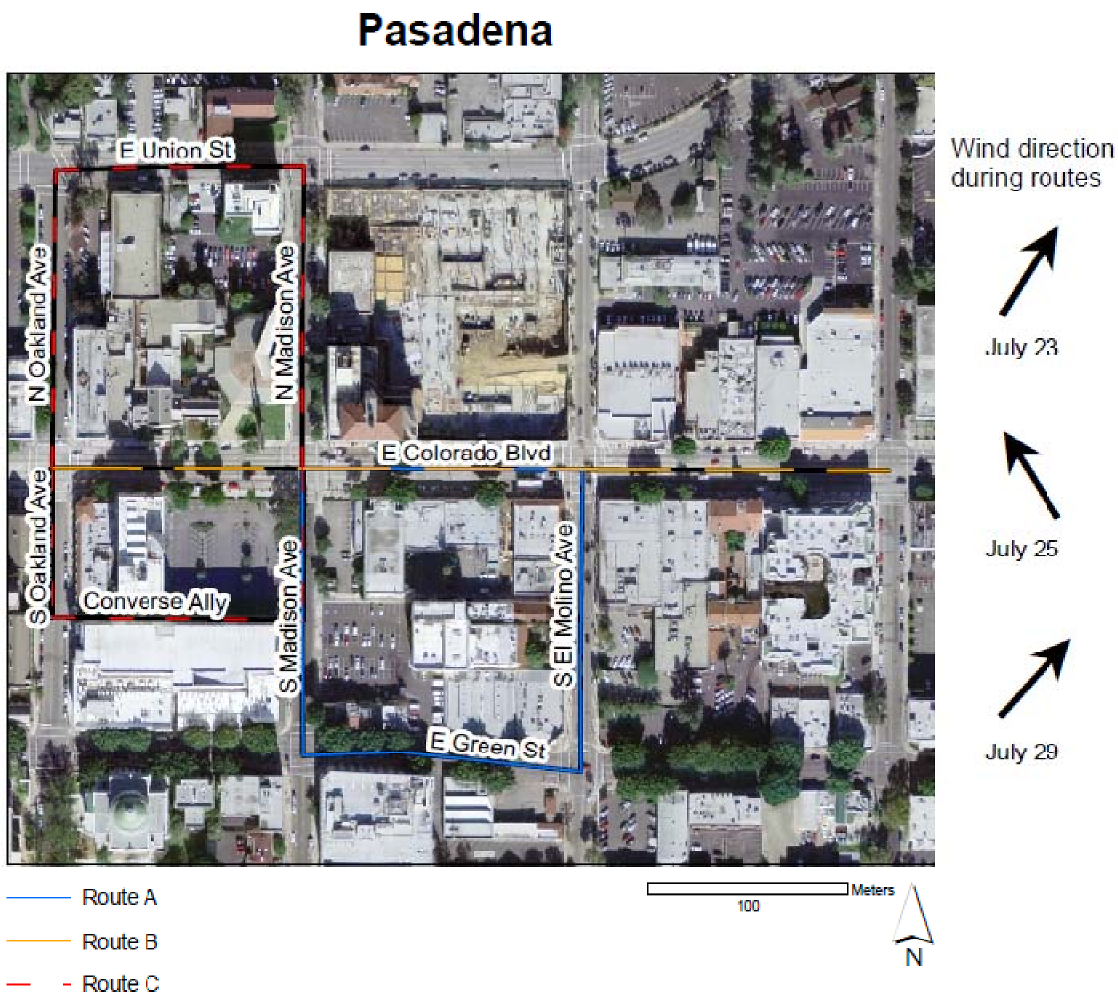

FIGURE 2 Pasadena study area and walkthrough routes.

Table 4 displays the results of two-sample t-tests comparing average $PM_{2.5}$ concentrations on opposite sides of the street for each case. The fifth column presents the sample difference in mean concentration and associated t-statistics for each route on each day. The sixth column displays the values of the same statistics obtained when we exclude the top one percent of measurements to eliminate outliers. The last two columns indicate the median wind direction and mean horizontal wind speed during each of the four cases.

TABLE 4 Two Sample T-Tests, Walkthrough Data for $PM_{2.5}$ Concentration

City	Route	Date	n	Difference in mean conc. (t-statistic)	Difference in mean conc., highest 1% excluded (t-statistic)	High conc. side of street	Median wind direction	Mean horizontal wind speed (m/s)
Huntington Beach	A	7/16/08	2370	3.40 (11.77)	2.78 (24.46)	South	216˚ (SW)	1.41
	A	7/18/08	1748	13.52 (20.96)	14.35 (76.41)	South	228˚ (SW)	1.18

	A	7/21/08	1624	8.19 (52.74)	8.01 (56.57)	South	259˚ (W)	1.60
	B	7/16/08	2360	4.82 (5.25)	1.59 (12.73)	East	221˚ (SW)	1.32
	B	7/18/08	2704	6.82 (41.16)	6.45 (64.71)	East	228˚ (SW)	1.12
	B	7/21/08	2456	10.46 (98.09)	10.41 (117.27)	West	259˚ (W)	1.58
Pasadena	B	7/23/08	2532	2.51 (2.44)	1.05 (7.62)	North	212˚ (SW)	1.21
	B	7/25/08	1792	0.39 (2.65)	0.10 (0.81)	South	142˚ (SE)	0.80
	B	7/29/08	2522	2.40 (13.75)	2.10 (13.41)	South	220˚ (SW)	1.66

The raw walkthrough $PM_{2.5}$ concentration data generally display a relatively uniform pattern throughout the walkthrough routes. As an example, Figure 3 shows walkthrough data, on both sides of Garfield Avenue, on July 18. The graph plots $PM_{2.5}$ concentration versus time separately for each side of the street for comparison. We zeroed the time scale and eliminated gaps between repeated passes of the same route for the sake of presentation.

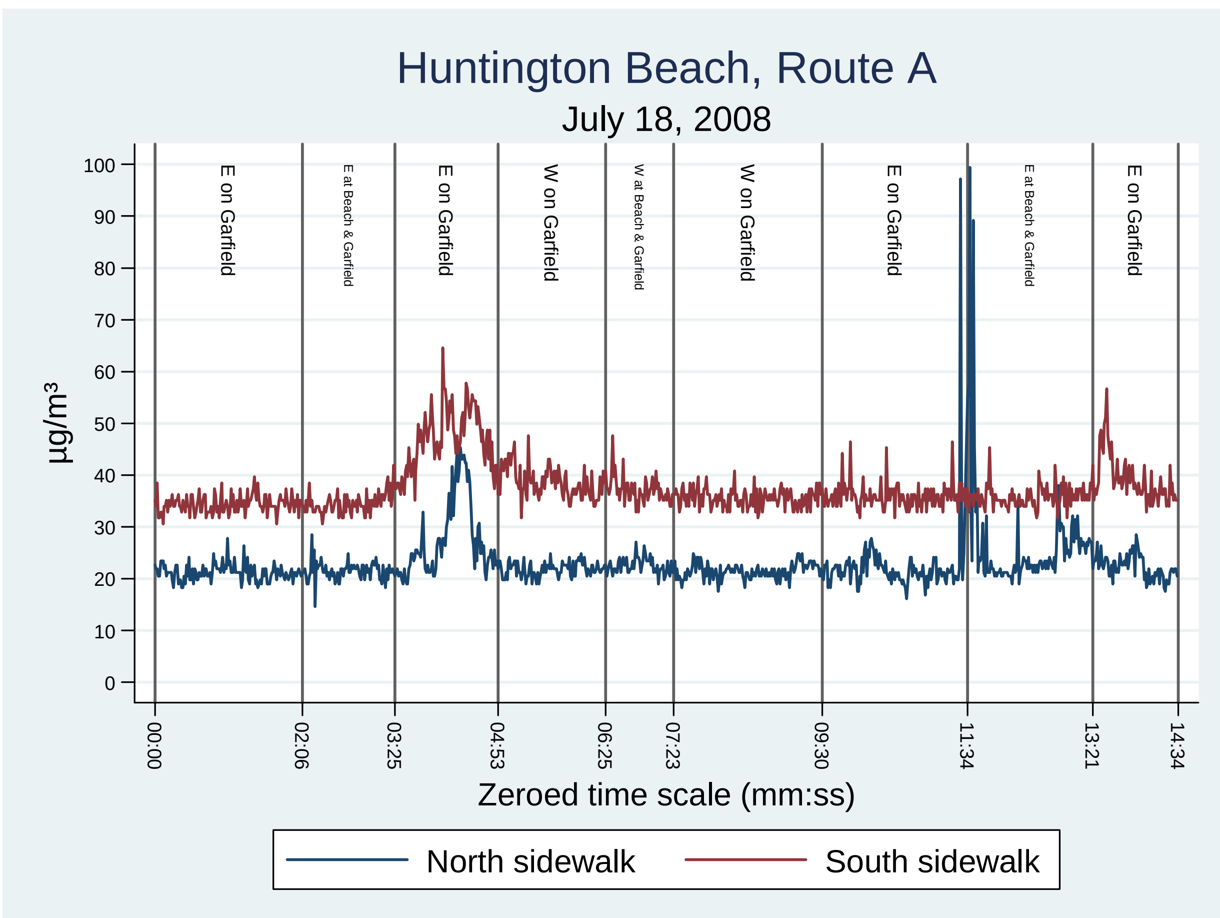

FIGURE 3 $PM_{2.5}$ Concentrations, Huntington Beach Route A, July 18.

In Huntington Beach for Route A (Garfield Avenue), the results show uniformly higher $PM_{2.5}$ concentrations on the south side of the street, which on all observation days was in the wind shadow of buildings (the wind was generally from a southwesterly or, on July 21, a west-southwesterly direction.) This is consistent with computer modeling results (*1*) that demonstrate the possibility that fine particulates can concentrate in eddies on the lee side (in the wind shadow) of buildings. The results from Route A in Huntington Beach provide empirical evidence and support our hypothesis that the built environment and meteorological conditions can interact in ways that trap or disperse particulates in urban settings. For Route B in Huntington Beach (Beach Boulevard), readings only differed by side of the street on two of the three days, with higher concentrations once on the east side and once on the west side. The east side of Beach Boulevard is not in the wind shadow based on wind direction on observation days, hence the July 21 Route B result for Huntington Beach is not consistent with the general pattern of results or with our hypothesis that particles are trapped in the wind shadow of buildings.

B. Comparison of Paired Stationary DustTrak Measurements

In addition to collecting data while walking, we also collected data for three two-hour periods each day at fixed locations. In some cases, the stationary DustTrak monitors were on opposite sides of the street or in a “windward / leeward” pattern that created the opportunity for DustTraks to be paired with one another, with one DustTrak in the pair in a building’s wind shadow while the other DustTrak in the pair is not. The locations of these paired DustTraks are shown in Figures 4-6.

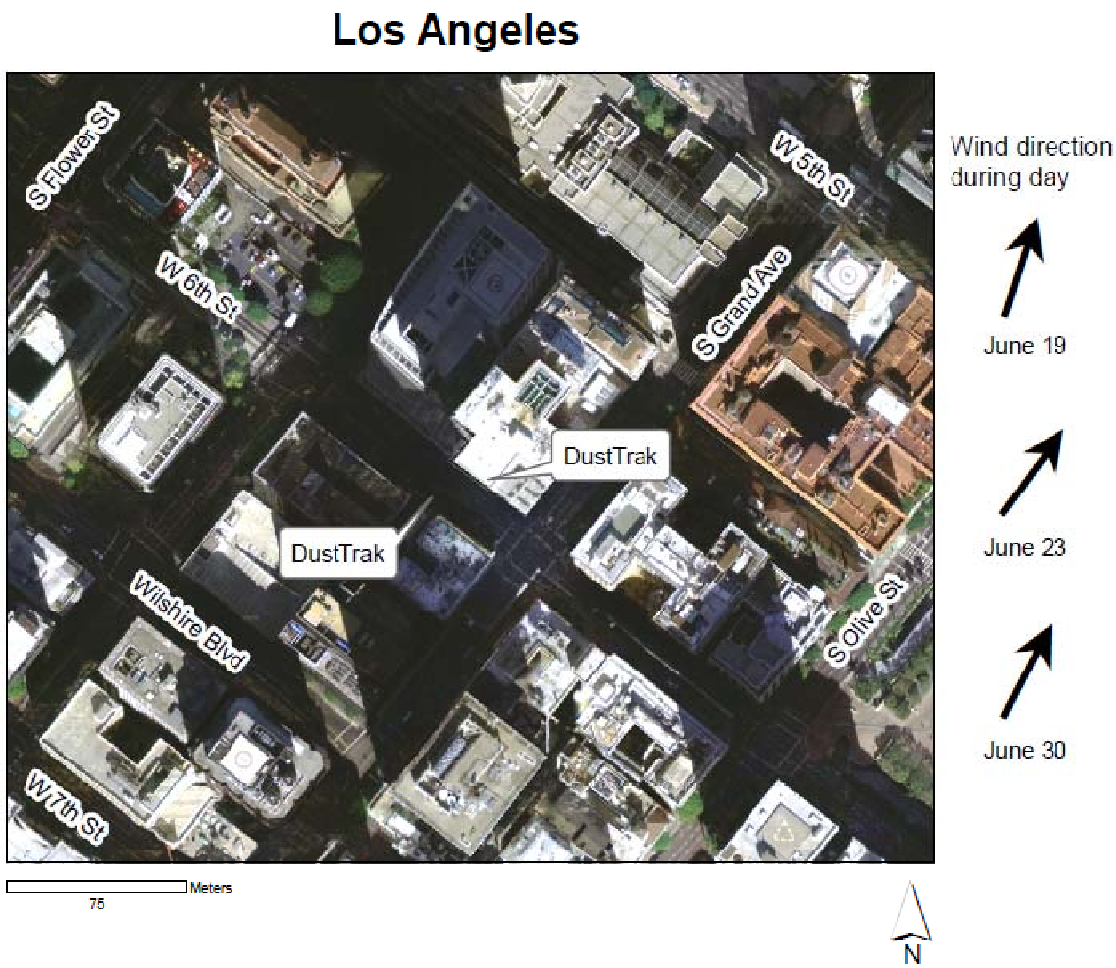

FIGURE 4 Paired DustTrak locations in Los Angeles study area.

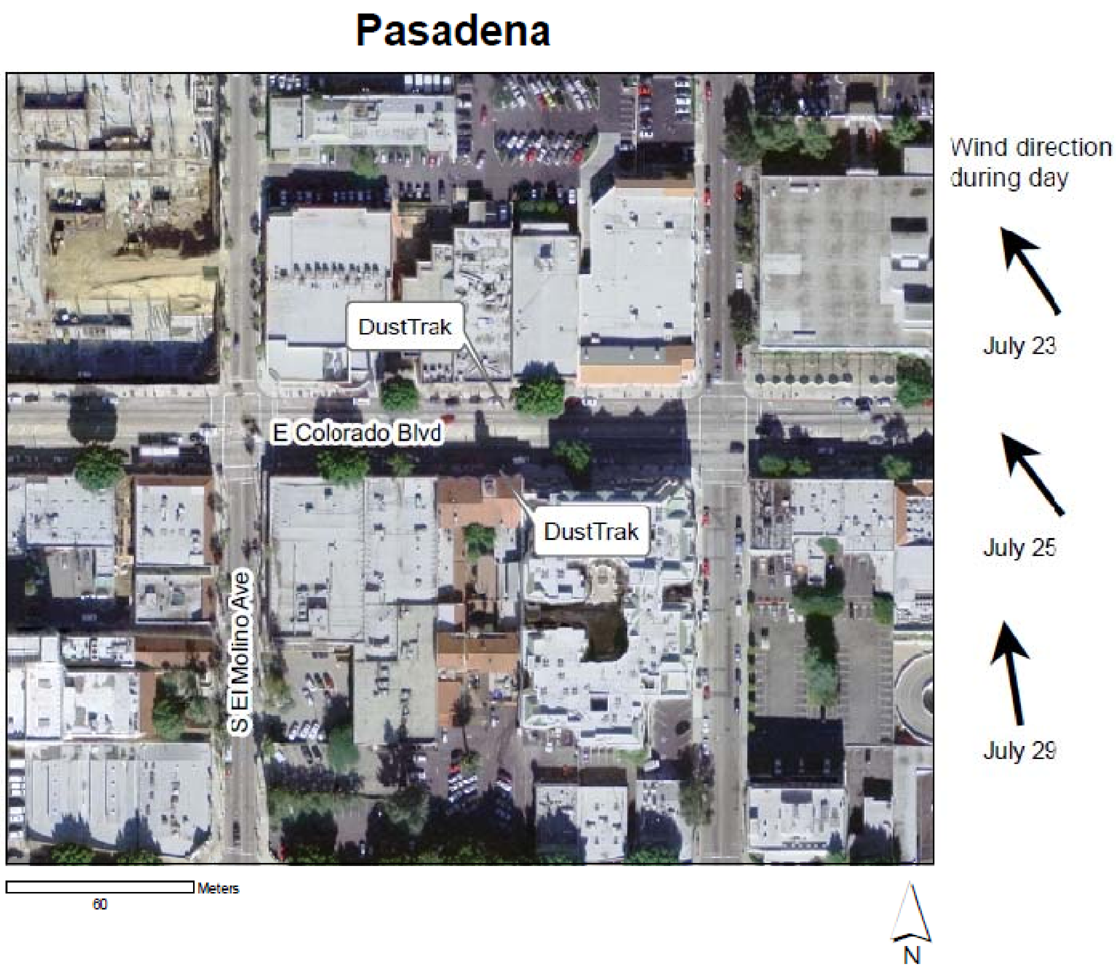

FIGURE 5 Paired DustTrak locations in Pasadena study area.

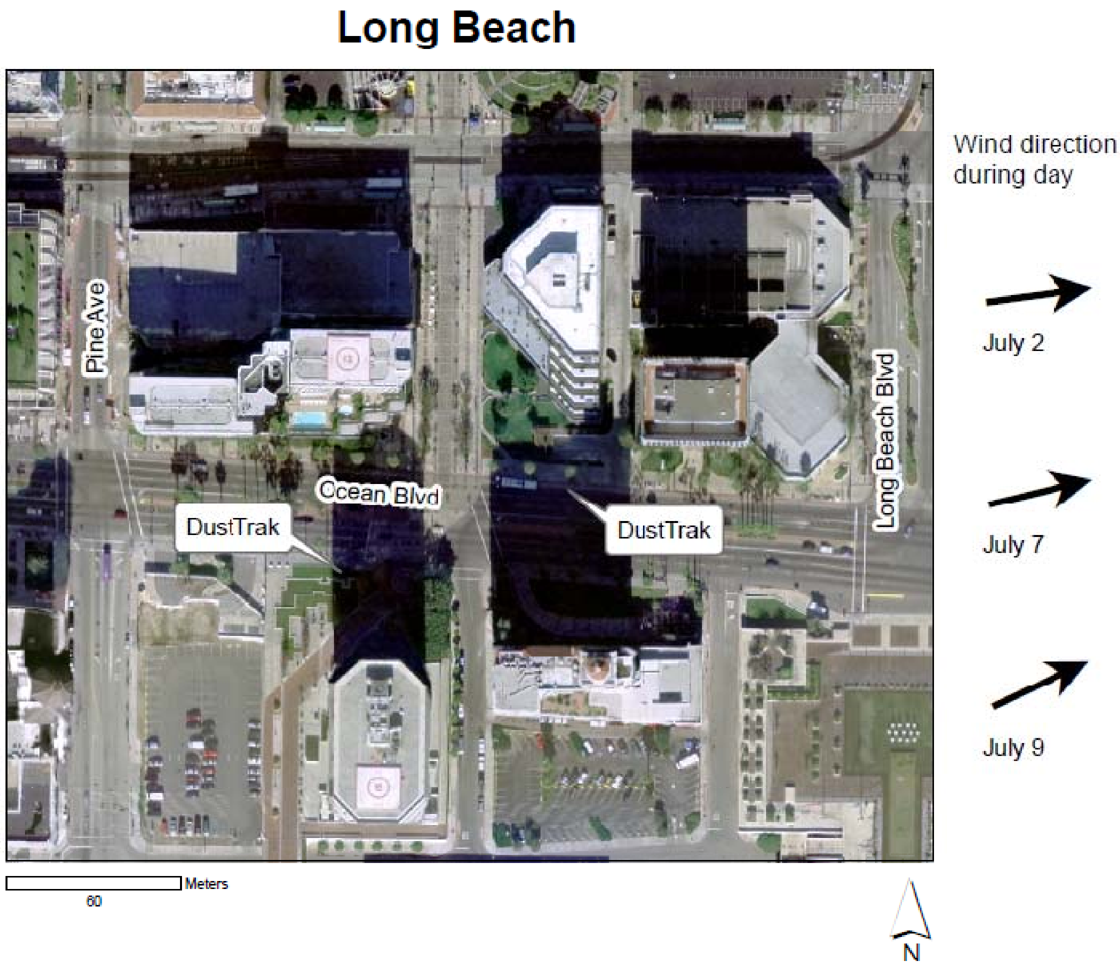

FIGURE 6 Paired DustTrak locations in Long Beach study area.

Table 5 displays results of two-sample t-tests comparing average particulate matter concentrations from sites on opposite sides of the street for three sites. In all but one case (Long Beach, July 9), statistically significant differences show higher concentrations on the "wind shadow" side of the street. Note that for Long Beach, the paired DustTraks are located, relatively to wind direction, in a manner that is a less good fit with an "upwind/downwind" or "wind shadow" configuration, and hence less weight might be attached to the Long Beach paired DustTrak results. For the other two study areas, the paired Stationary DustTraks give results that are consistently similar to the dominant pattern from the walkthrough data; locations in the wind shadow of buildings have higher $PM_{2.5}$ concentrations.

TABLE 5 Paired Stationary DustTrak $PM_{2.5}$ Concentration Comparisons

City	Date	Street	n	Difference in mean conc. (t-statistic)	Difference in mean conc., highest 1% excluded (t-statistic)	High conc. side of street	Median wind direction	Mean horizontal wind speed (m/s)
Long Beach	7/2/08	Ocean Blvd.	42,668	14.64 (86.95)	14.79 (94.85)	S	262˚ (W)	1.10
	7/7/08	Ocean Blvd.	42,792	7.20 (50.65)	6.79 (50.54)	S	256˚ (W)	0.86
	7/9/08	Ocean Blvd.	42,612	11.09 (91.55)	11.30 (>100)	N	244˚ (SW)	1.05
Los Angeles	6/19/08	6th St.	26,340	6.15 (15.65)	4.25 (63.94)	SW	198˚ (S)	0.69
	6/23/08	6th St.	41,911	1.94 (14.37)	1.31 (15.68)	SW	216˚ (SW)	0.79
	6/30/08	6th St.	42,017	3.79 (6.90)	1.55 (8.69)	SW	207˚ (SW)	0.77
Pasadena	7/23/08	Colorado Blvd.	42,659	3.10 (0.25)	2.35 (9.35)	S	146˚ (SE)	1.04
	7/25/08	Colorado Blvd.	42,200	2.52 (10.55)	1.64 (27.64)	S	143˚ (SE)	0.74
	7/29/08	Colorado Blvd.	42780	3.29 (27.87)	2.93 (26.01)	S	171˚ (S)	0.92

C. Regression Analysis

We next ran several regressions using the data from three cities for which parcel data is available: Long Beach, Los Angeles, and Pasadena. The dependent variable is the average one-second particulate matter concentration for each traversal of a street segment or intersection for all walkthrough data. There are multiple observations for each street segment and intersection because team members traversed each route multiple times and some routes share common segments. To provide a buffer between street segments and adjacent intersections, we calculated the average for street segments using only readings from the middle 50% of the segment.

The independent variables are:

- Cars per minute: Count of cars and light trucks divided by time span of the traversal in minutes
- Heavy trucks per minute: Count of delivery trucks or larger vehicles (except buses) divided by time span of the traversal in minutes
- Buses per minute: Count of buses divided by time span of the traversal in minutes
- Floor-area-ratio: Sum of built square feet divided by sum of parcel square feet for parcels within 70ft for street segments or 100ft for intersections
- Indicator variables for city, date, and whether the observation corresponds to an intersection

Table 6 displays the results of the regressions. Huber-White standard errors are in parentheses. Specification (a) includes only the traffic flow variables, the floor-area ratio, and the intersection indicator. All of the variables except for car flow have the opposite of the expected sign, perhaps due to confounding variables that differ among cities. To control for this, we include city indicator variables in specification (b). As expected, the city indicator variables are significant, but the explanatory variables of interest are no longer significant. In specification (c) we attempt to control for unobserved factors more thoroughly by including indicator variables for each day in addition to each city. The coefficient on floor-area-ratio alone becomes significant, and it is positive.

TABLE 6 Regression Results

Variable	(a)	(b)	(c)
Cars per minute	0.19***	0.03	0.02
	(0.04)	(0.03)	(0.02)
Heavy trucks per minute	-0.09	-0.23	0.12
	(0.62)	(0.36)	(0.15)
Buses per minute	-1.89***	-0.18	-0.06
	(0.32)	(0.13)	(0.10)
Floor-area-ratio	-1.45***	0.07	0.12*
	(0.11)	(0.06)	(0.06)
Intersection	-1.30	-0.45	-0.48
	(1.07)	(0.70)	(0.37)
Long Beach		7.31***	-8.38***
		(1.54)	(0.86)
Pasadena		24.97***	22.57***
		(0.59)	(0.56)
Date variables			3 of 4 significant at 0.001 level
Constant	41.20***	27.59***	28.73***
	(1.03)	(0.61)	(0.53)
n	654	654	654

*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

The floor-area-ratio (FAR) variable may, to some extent, be correlated with the study area dummy variables, but note that the FAR variable as constructed is a much more micro-measure of the built environment, smaller than the overall study areas.

Overall, we prefer the model that controls for both study area and day of observation. The clear differences in $PM_{2.5}$ concentration across study areas suggests the need to control for the study area. The association with weather patterns (particularly wind direction) suggests that it would be wise to control for at least macro meteorological effects through the (admittedly rough) method of including day dummy variables. The resulting model, in column (c), shows a significantly positive relationship between development intensity (FAR) and measured $PM_{2.5}$ concentrations, again providing evidence of an association between fine particulate concentrations and the built environment. The lack of an association with traffic intensity should not be regarded as definitive. Due to patterns of atmospheric transport and dispersion, temporal leads and lags for traffic may be important predictors of fine particulate emissions, and possibly traffic intensity may have to be interacted with wind speed and direction. We have not experimented with such considerations yet in a regression model.

V. CONCLUSION

At this point, the evidence suggests associations between fine particulate concentrations, wind direction, and building placement. We note that the built environment features that are apparently associated with $PM_{2.5}$ concentrations are as fine-grained as building-to-building variations, at geographic scales smaller than a city block. The differences in concentrations on opposite sides of the street averaged, in some cases, on the order of 10 $\mu g/m^3$. These differences are outside of current policy models of particulate concentration (e.g. Caline4), and hence outside of current policy discussions. Our results should inform both modeling and policy.

We do not believe that $PM_{2.5}$ concentrations should be used as a reason not to pursue compact development. The evidence here would not support such a strong policy conclusion, and any assessment of the appropriateness of compact development should include a comprehensive assessment of benefits and costs. Even a focus only on air quality would have to weigh the likely countervailing impacts of compact development on vehicle miles of travel and the effect of concentrating traffic and development in places where humans would be in closer proximity to $PM_{2.5}$ concentrations. Such analyses, and links from concentration to human exposure and to human health, would require considerably more evidence than is available here.

Our intention is to highlight the interaction of $PM_{2.5}$ concentrations and the built environment. The evidence here supports the hypothesis that fine particulate concentrations are influenced by the built environment in ways that are currently outside of modeling traditions and policy discussions. Furthermore, our results suggest that the association, while not uniform, may have enough regularity to lead to policy rules of thumb and modeling methods after further research.

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