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The effects of the built environment, traffic patterns, and micrometeorology on street level ultrafine particle concentrations at a block scale: Results from multiple urban sites

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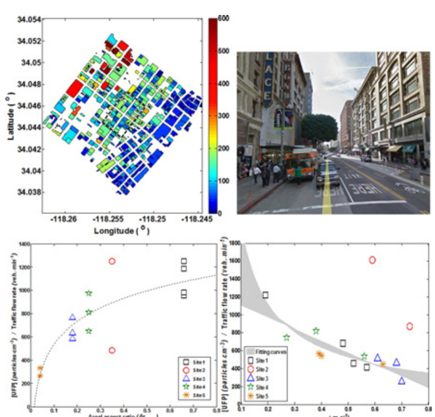
HIGHLIGHTS

- This study quantitatively examined built-environment effects on near-road UFP level.
- Block-scaled UFP conc. strongly depend on built environment and surface turbulence.
- Areal aspect ratio was a major contributor to UFP variations in the morning.
- Surface turbulence was a major contributor to UFP variations in the afternoon.
- Heterogeneous building morphology helps reduce UFP levels in the afternoon.

GRAPHICAL ABSTRACT



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ABSTRACT

This study attempts to explain explicitly the direct and quantitative effects of complicated urban built-environment on near-road dispersion and levels of vehicular emissions at the scale of several city blocks, based on ultrafine particle concentrations ([UFP]). On short timescales, ultrafine particles are an excellent proxy for other roadway emissions. Five measurement sites in the greater Los Angeles with different built environments but similar mesoscale meteorology were explored. After controlling for traffic, for most sampling days and sites, morning [UFP] were higher than those in the afternoon due to limited dispersion capacity combined with a relatively stable surface layer. [UFP] at the intersection corners were also higher than those over the sampling sites, implying that accelerating vehicles around the intersections contributed to [UFP] elevation. In the calm morning, the areal aspect ratio (Ar_{area}), developed in this study for real urban configurations, showed a strong relationship with block-scale [UFP]. Ar_{area} includes the building area-weighted building height, the amount of open space, and the building footprint. In the afternoon, however, when wind speeds were generally

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higher and turbulence was stronger, vertical turbulence intensity σ_w was the most effective factor controlling [UFP]. The surrounding built environment appears to play an indirect role in observed [UFP], by affecting surface level micrometeorology. The effects are substantial; controlling for traffic, differences in Ar_{area} and building heterogeneity were related to differences in [UFP] of factors of two to three among our five study sites. These results have significant implications for pedestrian exposure as well as transit-oriented urban planning.

1. Introduction

Vehicle emissions are rapidly diluted away from roadways, thus leading to highly spatially-heterogeneous pollutant concentrations in urban areas. A large fraction of the exposure of many individuals to many pollutants can be attributed to relatively short periods of time spent on and near roadways, which often have highly elevated pollutant concentrations compared to areas at even moderate distances from roadways (Behrentz et al., 2005; Fruin et al., 2004; Marshall et al., 2005; Morawska et al., 2008). However, because of the lack of adequate pollutant measurement data near roadways, studies of health effects attributed to transportation-related air pollutants have generally used freeway or arterial roadway proximity as a proxy for vehicle-related air pollution (Brugge et al., 2007; Ren et al., 2008; Volk et al., 2011; Zhou and Levy, 2007). Despite this rather blunt approach, near roadway pollution studies have shown moderate increases in a long list of adverse health outcomes, including increased incidence of cancer (Pearson et al., 2000), asthma (Janssen et al., 2003), general mortality (Hoek et al., 2002), heart attacks (Tonne et al., 2007), autism (Volk et al., 2011), pre-term birth (Ren et al., 2008) and other adverse outcomes associated with proximity to roadways.

Of a wide range of particle- and gas-phase species contained in fresh vehicular emissions, ultrafine particles (UFP; particles smaller than 100 nm in diameter) are one of the best tracers of near-roadway pollution, due to their large dynamic concentration ranges (10^3 to 10^6 particles$\cdot$cm^{-3}) and relatively short life time, which results in low and steady background concentrations (Capaldo and Pandis, 2001; Choi et al., 2013), and the availability of high time resolution (1 s) instrumentation that allows resolution of pollutant gradients controlled by complex dispersion.

Despite an increasing amount of literature related to near-roadway exposures, surprisingly little is known about how to proactively design and plan for these transit environments in order to minimize air pollution exposures. Therefore, it is desirable to develop a set of comprehensive recommendations on how to reduce pedestrian and residential air pollution exposures that will aid transportation and urban planners make future development plans. These may include traffic controls and urban building configuration, which impact emissions and dispersion, respectively. Within the transit environment, urban planners also decide spatially where pedestrian density will be greatest through their choices of where to site transit stops, sidewalks, and parks.

Several studies investigating the influence of the built environment on street level concentrations have been published recently, mostly focusing on deep street canyons and a few others. Four recent studies have taken the first step towards understanding dispersion of traffic-related pollutants in urban areas with inhomogeneous building morphology, which is our focus (Boarnet et al., 2011; Boogaard et al., 2011; Buonanno et al., 2011; Pirjola et al., 2012). Buonanno et al. (2011) focused on particles, including UFP, measured in four different street canyons with different building height-to-street width ratios (H/W = 0.5 to 1.3) in a town in central Italy; Pirjola et al. (2012) investigated dispersion of traffic emissions (focusing on UFP) in three different micro-environments (but with similar H/W ~ 0.5) in Helsinki, Finland; Boogaard et al. (2011) conducted an extensive study in the Netherlands in which five species, including particle number concentrations and black carbon, were measured over 6 weeks at 8 urban roadside locations in five cities; and Boarnet et al. (2011) examined the factors governing $PM_{2.5}$ measured on sidewalks next to arterial roadways in five cities in southern California.

Of these studies, Boogaard et al. (2011) and Boarnet et al. (2011) conducted stationary measurements of roadway pollutants, whereas Buonanno et al. (2011) and Pirjola et al. (2012) used a mobile platform to characterize UFP concentrations with a high temporal resolution. Boogaard et al. (2011) reported the two streets with buildings lining one or both sides of the streets showed the largest road contributions although their results did not discern the roles of meteorology, detailed building morphologies, and emissions. Boarnet et al. (2011) suggested the most effective controlling factors for sidewalk $PM_{2.5}$ concentrations are daily variations, time of day, winds, and temperature. They also argued that traffic and built environment variables accounted for only a small amount of variation, although they are statistically significant. However, their built environment variables were classified rather than quantified. After accounting for these most effective controlling factors, they concluded that street canyons with higher than 5-story buildings are related to high $PM_{2.5}$ concentrations, and adjacent paved lots were negatively associated with concentrations. Buonanno et al. (2011) and Pirjola et al. (2012) using mobile platform measurements, concluded that the surrounding built environment significantly affects pollutant concentrations in urban microenvironments by changing the dispersion. However, both studies considered only the averaged H/W and did not consider the detailed information of built environment such as the gaps between buildings and open spaces if any, and also did not quantitatively examine the role of built environment in pollutant concentrations.

While these studies provide insight into air pollution in built environments, the measurements lack the spatial resolution and completeness to discern contributions of detailed urban morphology and traffic control at a level that might inform highly-local planning decisions about the built environment and traffic flow regimes. Minimizing exposure to transportation-related air pollution is not fully considered currently in the process of planning for transit-oriented developments (TOD) (Haughey and Sherriff, 2010).

There are several relevant spatial scales to the investigation of the built environment with pollutant concentrations. Here we focus on a spatial scale of several city blocks. We develop quantitative links among the variables that control dispersion in complex urban environments, including building morphology, traffic flow rates, and micrometeorology. We consider data from five sites in the greater Los Angeles area, each with similar fleet composition and synoptic meteorology, but markedly different built environments and traffic flow patterns. Measurements were performed in both the early morning and mid-afternoon, which have significantly different atmospheric stability and wind profiles.

2. Methods

2.1. Sampling sites and built-environmental characteristics

Extensive field experiments, including mobile and stationary measurements of vehicular pollutants and traffic, were conducted at four sites in and around downtown Los Angeles (DTLA) and at a site in Temple City, located 20 km east of DTLA, for 16 days between July and November of 2013 (Fig. S1; Table 1). Each sampling site represents a distinct urban built environment with a different building morphology