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Where to locate transit stops: Cross-intersection profiles of ultrafine particles and implications for pedestrian exposure ☆

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A B S T R A C T

Epidemiological studies have shown that exposure to traffic-related pollutants increases incidence of adverse health outcomes. Transit users in cities across the globe commonly spend 15–45 min or more waiting at transit stops each day, often at locations with high levels of pollution from traffic. Here, we investigate the characteristics of concentration profiles of ultrafine particles (UFP) with 5 m spatial resolution across intersections, to determine the best place to site transit stops to minimize exposures. Cross-intersection UFP profiles were derived from 1744 profiles covering 90 m before and after each intersection center with a mobile monitoring platform. Measurements were made at 10 signalized intersections located at six urban sites, each with a distinct built environment, during both mornings and afternoons. Measurements were made within 1.5 m of the sidewalk and approximately at breathing height (1.5 m above ground level) to approximate sidewalk exposures. UFP profiles were strongly influenced by high emissions from vehicle stops and accelerations, and peaked within 30 m of intersection centers; from there concentrations decreased sharply with distance. Peak concentrations averaged about 90% higher than the minima along the block. They were accompanied by more frequent and larger transient concentration spikes, increasing the chance of people near the intersection being exposed to both short-term extremely high concentration spikes and higher average concentrations. The decays are somewhat larger before the intersection than after the intersection, however as siting transit stops after intersections is preferred for smooth traffic flow, we focus on after the intersection. Simple time-duration exposure calculations combined with breathing rates suggest moving a bus stop from 20 to 40–50 m after the intersection can reduce transit-users' exposure levels to total UFP substantially, in proportion to the reciprocal of the magnitude of elevation at the intersection.

1. Introduction

Epidemiological studies have attributed a long list of adverse health effects to exposures to air pollution around roadways, including increased incidence of cardiac and pulmonary events (Brugge et al., 2007; Tonne et al., 2007), diabetes-associated mortality (Raaschou-Nielsen et al., 2013), asthma and other respiratory symptoms (Janssen et al., 2003; Kim et al., 2002), autism (Volk et al., 2011), pre-term birth (Ren et al., 2008), and general mortality (Hoek et al., 2002).

Epidemiological studies have used proximity to roadways to estimate exposure because monitoring data for specific traffic-related pollutants is not available. As a result, evidence pointing to any specific component as the causative agent for health effects is inconclusive. However, ultrafine particles (UFP, particles smaller than 100 nm in diameter) have been implicated in several adverse health effects including respiratory and cardiovascular diseases and adverse birth outcomes (Hoek et al., 2010; Oberdörster et al., 2005; Penttinen et al., 2001). Further, while the health effects of short term exposure to elevated traffic-related pollutants are not yet well understood, a few studies have suggested that short-term exposure to elevated UFP aggravate existing pulmonary, respiratory, and cardiovascular conditions, and that repeated of short-term exposures such as from a daily commute may increase the risk of chronic diseases (Brugge et al., 2007; Cole-Hunter et al., 2012).

Here, we use UFP as a tracer for traffic-related pollution. UFP

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concentrations are an effective tracer for investigating roadway-emission distribution and dispersion due to their low background levels, large dynamic ranges associated with vehicle activity, relatively few competing sources. On the several-minute dispersion time scales of interest here, competing processes such as coagulation and deposition play a minor role for UFP (Choi and Paulson, 2016).

Because traffic-related pollutants are highly spatially heterogeneous in urban areas, individual exposures can depend strongly on relatively short stays in highly polluted micro-environments. For example, Goel and Kumar (2015a) estimated that drivers spend only 2% of their commuting time around intersections, but this short term exposure contributed ~25% of the total respiratory doses during their commutes by car due to elevated UFP concentrations around the intersections. Here, we focus on exposures of transit users (people who commute by public or private bus or light rail), waiting at stops on streets used by cars, trucks and busses. Transit users can spend substantial amounts of time waiting at stops; reporting between 14 and 56 min each day, with a median of 30 min (Table S1, data from Moovit (Moovit, 2017)).

Signalized traffic intersections are known to be hotspots of vehicular emissions due to high levels of stop-and-accelerate driving activities (Goel and Kumar, 2015b; Kittelson et al., 2006; Wang et al., 2008). Most previous studies, however were based on stationary measurements at a few of fixed points around the intersections (Holmes et al., 2005; Tsang et al., 2008; Wang et al., 2008), and did not provide detailed pollutant distributions from enhanced emissions.

A growing number of mobile monitoring studies have been conducted in recent years, but most studies have focused on pollution decay with distance from the source (Choi et al., 2012; Hu et al., 2009), in-cabin (Hudda et al., 2011), or free-flow on-road air pollution (Aggarwal et al., 2012). Only a tiny handful of studies have investigated highly spatially resolved concentration profiles of roadway emissions in micro-environments such as intersections or roadways with different built environments (Choi et al., 2016; Goel and Kumar, 2015b; Ranasinghe et al., 2016), despite their important implications for transit-oriented development and related exposure of pedestrians, residents, and transit users to roadway emissions.

Recently, Goel and Kumar (2015b) estimated significant ranges for the 'zone of influence' (ZoI, the area for which there was a clear impact from the intersection on pollutant concentrations; 79–129 m) for UFP from 10 three- and four-way signalized traffic intersections. They focused more on the length of ZoI, the mean concentrations within the ZoI, and the contributions of different driving conditions to the total UFP concentrations, all of which showed wide variations at different intersections. This specificity limits somewhat general applications of their findings to transit-oriented urban planning strategies.

A few studies have considered exposures of pedestrians and cyclists on sidewalks and bicycle paths, and have investigated the similarity of pollutant concentrations on the paths or sidewalks and the roadway. Pattinson et al. (2017) used bicycle-mounted instruments to estimate exposure levels in separated bicycle-lanes near roadways, and reported 20–30% and 40–50% exposure reductions in sidewalks and off-road bicycle lanes separated 7 m and 19 m from the roadways, respectively. Their roadway and cycle path measurements were not made simultaneously, leading them to suggest their results could be influenced by other localized factors such as interactions between air flows, buildings, traffic speed and composition, rather than distance from the roadway. These results suggest a faster decay than has been observed by many near-highway plume decay measurements (~10% at 10 m, from Fig. 3 in (Karner et al., 2010)) for perpendicular winds. The distance dependence of UFP concentrations within street canyons is more complicated. For example, Pirjola et al. (2006) showed the difference in UFP concentrations between at the edge and at 15 m from the road edge was insignificant, and similarly, Rakowska et al. (2014) also showed slightly increased UFP concentration at roadside compared to on-road in a complex urban environment. Many modelling studies for street canyon environments showed significant pollutant concentration variations at both sides of the street surrounded by buildings due to in-canyon vortices (e.g., Gallagher, 2016; Kim and Baik, 2004). Taken together, these studies suggest that concentrations at the edge of the roadway and 0.5–3.5 m away on the adjacent sidewalk do not differ significantly.

In this study, we obtain highly resolved UFP concentration profiles across 10 signalized four-way intersections with mobile measurements. The sites had wide range of different built environments found in the greater Los Angeles area. Mobile measurements have a great advantage in sampling data at high spatial and temporal resolution (1s) and thus make it possible to investigate micro-environment effects. However, mobile measurements can be affected by high-emitting vehicles ahead and thus pedestrian exposure can be over-estimated due to sampling position (Pattinson et al., 2017; Woo et al., 2016). We minimize this source of bias by driving mostly in the lane adjacent to the sidewalk and placing the inlet at 1.5 m on the sidewalk side of the mobile platform. Further, there is little evidence for significant differences in concentrations at the inlet and on the sidewalk 0.5–3.5 m away from the inlet (above). UFP concentration profiles we report cover 90 m before and after each intersection center, and were derived from 891 morning profiles (periods with relatively stable atmospheric conditions) and 853 afternoon profiles (periods with mostly unstable atmospheric conditions). With this large number of UFP profiles, we investigate the general characteristics of air pollutants from enhanced vehicular emissions caused by stops and accelerations at the intersections. With this generalized pollutant distribution around intersections, we further investigate transit-user's exposure level to UFP in intersection micro-environments. We find the minima after the intersections (the 'far side'), as transit stops are preferentially sited after the intersections by transportation planners due to numerous advantages related to traffic flow over placement before intersections (the 'near side') (Diab and El-Geneidy, 2015) (see Section 4 for more details).

To our knowledge, this study provides, for the first time, generalized highly resolved UFP concentration profiles around the intersections. This has significant implications for improving our understanding of pedestrian exposure to elevated roadway emissions at the intersections, and the implications for improving strategies for transit-oriented development and urban planning. Because bus stops are typically located near intersections, understanding the spatial distributions of air pollutants from emissions around the intersections has potential to reduce pollution exposure outcomes.

2. Methods

2.1. Sampling sites and built environments

Mobile measurements of ultrafine particles were conducted in variety of urban configurations in the greater Los Angeles area in the summer through late fall of 2013 and summer 2014. The 2013 sampling areas include four sites in and around downtown Los Angeles (DTLA), and one in Temple City (20 km east from DTLA). Each sampling site covers a 2-by-2 block area centered on an intersection, and represents a distinct urban configuration with a different building morphology common in the United States. They include a typical street canyon, a site with flat and low buildings,