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Population exposure to ultrafine particles: Size-resolved and real-time models for highways

Shanjiang Zhu [a], Julian D. Marshall [b], David Levinson [c,d,*]

[a] George Mason University, Department of Civil, Environmental and Infrastructure Engineering, 4400 University Drive, Fairfax, VA 22030, United States
[b] University of Washington, Department of Civil and Environmental Engineering, United States
[c] University of Minnesota, Department of Civil, Environmental and Geo- Engineering, United States
[d] University of Sydney, School of Civil Engineering, Australia

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ABSTRACT

Prior research on ultrafine particles (UFP) emphasizes that concentrations are especially high on-highway, and that time on highways contribute disproportionately to total daily exposures. This study estimates individual and population exposure to ultra-fine particles in the Minneapolis – St. Paul (Twin Cities) metropolitan area, Minnesota. Our approach combines a real-time model of on-highway size-resolved UFP concentrations (32 bins, 5.5–600 nm); individual travel patterns, derived from GPS travel trajectories collected in 144 individual vehicles (123 h at locations with UFP estimates among 624 vehicle-hours of travel); and, loop-detector data, indicating real-time traffic conditions throughout the study area. The results provide size-resolved spatial and temporal patterns of exposure to UFP among freeway users. On-highway exposures demonstrate significant variability among users, with highest concentrations during commuting peaks and near highway interchanges. Findings from this paper could inform future epidemiological studies in on-road exposure to UFP by linking personal exposures to traffic conditions.

1. Introduction

Exposure to particulate matter (PM) is associated with respiratory and cardiovascular disease (e.g. Dockery (2001), Pope et al. (2002)). Ultrafine particles (UFP; PM with diameter less than 0.1 μm) have drawn increasing research interest because, relative to other particles, UFP can be more toxic to lab animals (Donaldson et al., 1998; Warheit et al., 2006), be harder to be removed by macrophages in the lung (Jaques and Kim, 2000; Oberdörster et al., 2005), and more easily enter the circulatory system and travel to the heart, brain, and other organs (Oberdörster et al., 2004). While larger particles are often measured based on mass, UFP typically are measured in terms of the number of particles (PN). Polluted air typically has many UFP (in terms of number [typical values: $\sim 10^4$–10^6]) yet their total mass is small (typical total mass for UFP is less than 1 $\mu g\ m^{-3}$) (Sioutas et al., 2005; Seinfeld and Pandis, 2012).

Urban traffic, especially heavy-duty diesel freight, is a major source of UFP emissions and exposures (e.g. Shi et al. (2001), Wahlina et al. (2001) Terzano et al., 2010). Harrison et al. (2011) showed factors related to the emissions on one road in central London accounted for 40.5% of particle volume and 71.9% of particle number, and revealed that solid carbonaceous particles from diesel exhaust was the largest contributor to particle number (38%) and second to particle volume (18.8%). On-road measurements (Morawska et al., 1999; Zhu et al., 2002a, 2002b) indicate that UFP concentrations are much higher

* Corresponding author at: University of Minnesota, Department of Civil, Environmental and Geo- Engineering, United States.
E-mail addresses: szhu3@gmu.edu (S. Zhu), jdmarsh@uw.edu (J.D. Marshall), dlevinson@umn.edu (D. Levinson).

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on-road than the urban background, and concentrations decline rapidly away from highways. For example, for the I-405 freeway in Los Angeles, CA, Zhu et al. (2002a) report an order of magnitude drop in UPM concentrations (6–220 nm) between 30 m ($100–200 \times 10^3$ cm^{-3}) and 300 m ($30–40 \times 10^3$ cm^{-3}) from the freeway. Concentrations at 300 m were indistinguishable from upwind background. Results for the I-710 in Los Angeles were similar (Zhu et al., 2002b). More recently, Hagler et al. (2010) showed that median UFP level in near road areas (20–150 m) were a factor of 1.8–1.2 higher than urban background. Wang and Gao (2011) found PM2.5 number concentration reached the peak on street side, but the mass concentration was the highest on subway trains using data collected in the New York City. Studies have compared UFP concentrations by mode (e.g., car, subway, and bicycle) (Both et al., 2013; Boogaard et al., 2009; Kaur et al., 2005; Kingham et al., 2007; Knibbs and de Dear, 2010; Ragettli et al., 2013). A comprehensive review of studies in the field of UFP is provided by Morawska et al. (2008), Knibbs et al. (2011), and Kumar et al. (2011).

Measurements by Kaur and Nieuwenhuijsen (2009) of UFP in London, found that exposures are correlated with average hourly bidirectional traffic flow. Wallace and Ott (2011) measure UFP exposure in two cars on 17 trips on major highways on the East and West Coasts of the United States; they concluded that in-vehicle exposures represent 17% of the total daily exposure for a typical suburban nonsmoker. In contrast, Fruin et al. (2008), studying on-road concentrations and average driving time, conclude that 33–45% of total UFP exposure for Los Angeles residents occurs during traveling in vehicles, which only accounts for 6% of the time. Their results emphasize that because concentrations and number of people on-roadway vary in time and space, estimates based on average values are not accurate. Westerdahl et al. (2005) pointed out that further studies are needed to quantify the influence of traffic, route, vehicle ventilation and meteorological influences. de Nazelle et al. (2012) compared the exposure of travelers in different modes using data collected from Barcelona and showed car riders on average had the highest exposure. Both et al. (2013) conducted a similar study in Jakarta, Indonesia based on samples collected from 36 individuals and concluded the exposure for public transport riders was higher than car riders. Quiros et al. (2013) modeled UFP exposure using data collected along a 1-km urban residential roadway, in Santa Monica, CA. Hudda et al. (2012) tried to correlate the in-vehicle ultrafine particle exposures to on-road concentrations using data collected from 43 vehicles. Xu and Zhu (2013) further investigated several ways to reduce the in cabin exposure to UFP. For health implications related to UFP exposure, Kubesch et al. (2014) showed that traffic-related UFP exposure would slightly increase diastolic blood pressure based on a two-hour real world experiment with 28 participants. A similar study showed detectable impact of traffic-related pollutants (UFP is one of them) on lung function Kubesch et al. (2013). Many studies called for more effort to provide better estimates of on-road exposures to UFP for both individual travelers and the general public.

To bridge this gap, this study evaluates both population and individual exposure to UFP on freeways in the Minneapolis – St. Paul (Twin Cities) metropolitan area, Minnesota. Most previous studies focus either on emission models, or on individual UFP exposure at a few limited locations. None of these studies investigated the network-wide impact to the general public as a whole. In our work, we estimate size-resolved exposures for during 44 days in year-2008 for 100% of the highway-vehicle population and then separately for a sample of vehicles for which we have GPS-recorded travel times and locations. We employ a UFP concentration model, which was previously developed by Aggarwal et al. (2012) to associate on-road UFP concentration with traffic volume and speed. The next section briefly describes the concentration model used in this paper. The pattern estimated UFP concentration and exposure is presented and discussed. Findings from this research advance our understanding of personal exposure to UFP and may inform future UFP exposure studies.

2. Methods

The objective of this study is to estimate on-highway exposure to UFP for individuals and the general public. UFP are generally measured as number concentrations (e.g., number of particles per cm^{-3}). Particle sizes (e.g., nm) refer to aerodynamic diameter; size ranges refer to particles with diameters between the lower and upper ends of that range. The use of size ranges is necessary when talking about environmental concentrations. For example, all else being equal, one would expect more particles in a wider size range than in a narrower size range (e.g., more particles between 60 nm and 70 nm than between 60 nm and 61 nm or between 60.0 and 60.1 nm). Our use of the term "exposure" refers to on-freeway air; others have investigated the relationship between concentrations on-freeway and in-vehicle (Hudda et al., 2011, 2012; Hudda and Fruin, 2013; Knibbs et al., 2010; Qi et al., 2008). Reasons for considering particle size distributions – as is done here – include that different sizes may come from different sources, may interact differently in the environment and (after being inhaled) inside the body, and may have different health impacts.

Since traffic congestion usually implies both high UFP exposure per capita and high traffic flow, the combination of which suggests high exposure of the public as a whole. Therefore, this study combined historical data for traffic conditions documented by the Minnesota Department of Transportation (MnDOT) and on-road UFP concentration collected through a sample to model UFP concentration on the Twin Cities network. Exposure of freeway users to UFP can then be estimated based on the same traffic count data. This study also differentiates from previous studies by providing insights on individual en-route exposure to the UFP using individual GPS travel trajectory collected at the Twin Cities. This approach allows minute-to-minute modeling of UFP exposure as people travel within the urban freeway microenvironment, revealing spatial and temporal patterns of individual UFP exposure with high details.

The study location is the Twin Cities (Minneapolis, St Paul), Minnesota. To estimate on-road concentrations, we employ publicly available real-time traffic data and a prior model by Aggarwal et al. (2012) that predicts real-time size-resolved UFP

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