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Cyclist exposure to UFP and BC on urban routes in Antwerp, Belgium

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HIGHLIGHTS

- Mobile monitoring with a bicycle is performed in an urban environment.
- Large spatial and temporal variations in UFP and BC concentrations are observed.
- Traffic and street topology are determinant for cyclist exposure to air pollution.
- Localized peak events have significant impact on the integral cyclist exposure.

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ABSTRACT

Ultrafine particles (UFP) and black carbon (BC) concentrations show a highly dynamic micro-variability in urban area. Mobile monitoring using a bicycle platform (354 runs in 1 month) was adopted in this study to characterize the micro-variability in relation to traffic intensity, street topology and meteorological conditions. For UFP and BC a positive relationship was demonstrated between pollutant concentration and traffic intensity. In addition, the distance to the traffic and the street topology were the dominant factors influencing the UFP and BC concentrations. A high variability between streets and even within streets was observed, and also between days and hour of the day. The exposure of cyclists in urban environments is strongly linked to the spatio-temporal variability of the pollutant concentrations. Fixed-track comparisons through time revealed significant differences in exposure between days and hour of the day, but even more importantly due to the occurrence of peak concentrations along the cycling track. Peaks were mainly found near busy cross-roads and in tunnels.

1. Introduction

Particulate air pollution is a mixture of particles that vary in number, size, shape, surface area, chemical composition, solubility and origin. Particulate matter in the urban air is introduced by primary emissions from combustion sources in transportation, industries and power generation, and by secondary formation through atmospheric photochemical reactions and conversion processes (Seinfeld and Pandis, 2012). UFPs are commonly defined as particles having a diameter of less than 0.1 μm. UFPs have a transient nature with short life times and rapidly grow through atmospheric processes of coagulation and/or condensation to larger complex aggregates (Pope and Dockery, 2006). These dynamics induce important differences, in space and time, of UFP concentrations between urban micro-environments (Moore et al., 2009; Hudda et al., 2010). Typically the highest concentrations are in the vicinity of the primary sources (Nikolova et al., 2011), for example, near busy roads where they are typically between 10^4 and 10^6 pt/cm^3 depending on driving speed, fleet composition and meteorology. UFP number concentrations decrease rapidly with distance from the emission sources (Zhu et al., 2008; Hagler et al., 2010). Hu et al. (2012) observed elevated UFP concentrations across residential areas in Los Angeles. Pollutant concentrations varied significantly over seasons, days and hour of the day. Within the residential area, however, UFP concentration did not exhibit strong spatial gradients due to a spatially quite homogeneous UFP distribution which has been attributed to high traffic volumes, substantial numbers of high-emitting vehicles and the high density of stop signs and lights requiring frequent acceleration of vehicles.

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Black carbon (BC) is a constituent of fine particles. BC is a primary particle that is emitted from incomplete combustion as tiny spherules ranging in size between 0.001 and 0.005 μm, and aggregates to particles of larger size (0.1–1 μm) (EPA, 2010). Typically, BC concentrations range between a few μg/m^3 in moderately polluted urban environments to a few tens of μg/m^3 in heavily polluted areas under unfavourable meteorological conditions (studies cited in Viidanoja et al. (2002)). A seasonal and inter-annual variability in BC concentration at an urban location was demonstrated by Ganguly et al. (2006). In an urban environment a sharp day-to-day variation in BC concentration is observed, and is dominated by factors as wind speed and mixing height, while the dominant sources of BC stay relatively stable throughout the year (Viidanoja et al., 2002). The within-day variability of BC on a road and highway environment was largely explained by diesel truck density and hour of the day (as proxy for wind speed) in a study in Los Angeles (Fruin et al., 2008). From 27 measurement locations along highways in New York, Maciejczyk et al. (2004) observed a high difference in daily median BC concentrations between week- and weekend days (1.7–12 μg/m^3 and 0.5–2.9 μg/m^3), with a large spatial variability. In another study in New York, Venkatachari et al. (2006) found that the concentration of BC varies in response to the interplay of source activity, meteorological conditions, and spatial factors.

UFP and BC share the same combustion-related emitting sources in urban environments. Additionally, significant UFP formation by photochemical formation from precursor aerosols has been observed in residential areas (Hu et al., 2012). The correlation between UFP and BC has been investigated in several studies. Westerdahl et al. (2005) report a high correlation ($R^2 = 0.76$) at a 60-s time resolution based on mobile measurements in the Los Angeles area with a TSI Condensation particle counter and Magee Scientific Aethalometer Model 42. In another study based on mobile measurements in a provincial town in Belgium (Van Poppel et al., 2013) the correlation (R^2) between UFP measured with P-Trak (TSI, model number 8525) and BC measured with Magee Scientific micro-aethalometer was 0.41, based on averages per traffic zone for individual runs. Hagler et al. (2009) report a high correlation ($R^2 = 0.65$) between 10-min averaged UFP and BC measurements made with P-Trak and a Magee Scientific AE4 Aethalometer for a near road sampling campaign at a major roadway in Raleigh, North Carolina with traffic intensities of 125,000 vehicles per day.

Vehicle transport emissions results in elevated downwind concentrations of UFP, BC (or related parameters) and other pollutants. (see also Van Poppel et al., 2013 and references therein). Exposure to these pollutants is strongly influenced by the time spent in traffic and the daily activity pattern in relation to transportation mode. In a study of Fruin et al. (2008) 33–45% of the daily UFP exposure for Los Angeles residents occurs due to time spent travelling in vehicles. Dons et al. (2012) observed that exposure to BC in traffic accounted for 21% of total exposure. Increased short-term exposure of cyclists to traffic pollutants has been observed to change heart rate variability and respiratory function (Weichenthal et al., 2011). Evidence for health hazards for people living or spending substantial time near highways is given in the review study of Brugge et al. (2007). An elevated risk for development of asthma and reduced lung function in children was observed in relation to an increased exposure to traffic pollution.

Air pollution monitoring from mobile platforms is increasingly applied for exposure monitoring. Two tracks in using mobile measurements for exposure assessment are encountered in the literature. The larger number of exposure studies applies personal monitoring by equipping the study subjects with portable integrated sampling equipment or real-time monitors. For example, this type of mobile measurements are used to assess the personal exposure to BC of individuals during their daily activities (Dons et al., 2012), to monitor bus-related micro-environments for commuting school children (Behrentz et al., 2005) or to quantify the exposure to $PM_{2.5}$ and elemental carbon in an urban environment for children with asthma (Spira-Cohen et al., 2010) or assess exposure while commuting (Dons et al., 2013; Kingsham et al., 2013). As concluded from the study of Kaur et al. (2005) the added value of personal monitoring is pollutant dependent. UFP number concentration and carbon monoxide (CO) concentration were much higher from personal monitoring in comparison to the measurements from a fixed monitoring station at background or kerbside location. In contrast, the differences between the personal mobile and the fixed monitoring were not significant for $PM_{2.5}$ in which case measurements from a fixed station could be used to estimate personal exposure accurately. A second group of studies addresses the potential of using mobile measurements to construct air pollution maps at a high spatial (and temporal) resolution and to derive exposure to pollutants from these maps. Hu et al. (2012b) equipped an electrical vehicle with fast response UFP, BC and NO measurement devices, and indicate the potential use of the high-resolution data for epidemiological studies. Padró-Martínez et al. (2012) gathered an extensive high-resolution dataset from mobile monitoring to study temporal (daily, weekly, seasonal) and spatial patterns of different air pollutants near highway neighbourhoods. The integration of high-resolution data from mobile sensing in epidemiological research, however, stays a challenging task. The high variability in pollutant concentration in relation to the distance to sources or to the travelling mode, and the heterogeneity of activity patterns complicate the full exploitation of these high-resolution pollution data for exposure studies. Additionally, deriving high-resolution maps from mobile data requires large quantities of data to represent the range of possible meteorological and traffic conditions (Padró-Martínez et al., 2012) and to aggregate very localized spatio-temporal snap-shot into broader-scale pollution maps (e.g. by monitoring in repeated runs (Peters et al., 2013)).

The objective of this study is to examine UFP and BC pollution data from mobile monitoring at different scales. A multiscale approach is taken to investigate (i) the spatio-temporal variability of UFP and BC concentration in the urban environment, (ii) to study the correlation between UFP and BC and (iii) to assess the potential of mobile monitoring for exposure assessment of a cyclist. The temporal detail ranges between weeks, day and hour of the day. Spatially, the data are treated at the suburban scale, the street level and up to a 10 m resolution. Although this study is confined in space and time, results could be generalized to other, potentially more extensive, cases.

2. Material and methods

2.1. Mobile monitoring in an urban environment

A monitoring campaign using a mobile monitoring platform, the Aeroflex (Elen et al., 2013), was setup in Antwerp (51°12′N, 4°26′E), Belgium. The Aeroflex is a bicycle equipped with compact air quality measurement devices to monitor ultrafine particle number concentration and black carbon concentration at a high resolution (up to 1 s). Each measurement is automatically linked to its geographical location and time of acquisition using GPS (GlobalSat BU-353) and internet time. Two air pollutants were monitored in this study: ultrafine particles (UFP, measured as particle number concentration (PNC), pt/cm^3) and black carbon (BC in μg/m^3). A TSI P-Trak ultrafine particle counter (model number 8525) was used to measure the number concentration of UFP (size range 0.02–1 μm)