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Exposure to air pollutants during commuting in London: Are there inequalities among different socio-economic groups?

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ABSTRACT

People with low income often experience higher exposures to air pollutants. We compared the exposure to particulate matter (PM_1, $PM_{2.5}$ and PM_{10}), Black Carbon (BC) and ultrafine particles (PNCs; 0.02–1 μm) for typical commutes by car, bus and underground from 4 London areas with different levels of income deprivation (G_1 to G_4, from most to least deprived). The highest BC and PM concentrations were found in G_1 while the highest PNC in G_3. Lowest concentrations for all pollutants were observed in G_2. We found no systematic relationship between income deprivation and pollutant concentrations, suggesting that differences between transport modes are a stronger influence. The underground showed the highest PM concentrations, followed by buses and a much lower concentrations in cars. BC concentrations in the underground were overestimated due to Fe interference. BC concentrations were also higher in buses than cars because of a lower infiltration of outside pollutants into the car cabin. PNCs were highest in buses, closely followed by cars, but lowest in underground due to the absence of combustion sources. Concentration in the road modes (car and bus) were governed by the traffic conditions (such as traffic flow interruptions) at the specific road section. Exposures were reduced in trains with non-openable windows compared to those with openable windows. People from less income-deprived areas have a predominant use of car, receiving the lowest doses (RDD < 1 μg h^{-1}) during commute but generating the largest emissions per commuter. Conversely, commuters from high income-deprived areas have a major reliance on the bus, receiving higher exposures (RDD between 1.52 and 3.49 μg h^{-1}) while generating less emission per person. These findings suggest an aspect of environmental injustice and a need to incorporate the socioeconomic dimension in life-course exposure assessments.

1. Introduction

Air pollution is considered a major threat to human health because of its link to an increased mortality and loss of disability-adjusted life years (GBD 2013 Risk Factor Collaborators, 2015). Combustion emissions, especially particles in various size ranges, are suspected to be particularly harmful (Heal et al., 2012; HEI Panel on the Health Effects of Traffic-Related Air Pollution, 2010; WHO, 2013). Black carbon (BC) is considered a better tracer of traffic emissions than particulate matter (PM) mass (Reche et al., 2011; WHO, 2012), especially for diesel-fuelled vehicles. Owing to their size, ultrafine particles (<100 nm) may affect human health more strongly than larger-sized particles (Chen et al., 2016a, 2016b; Kumar et al., 2014; Lanzinger et al., 2016) and should be included in exposure assessments next to other pollutants.

Commuters are particularly affected by traffic-related air pollutants owing to their proximity to the source. BC and particle number concentrations (PNCs) represent ultrafine particles, which decrease exponentially downwind away from the road/highway (Fujitani et al., 2012; Kim et al., 2002; Zhu et al., 2006; Zhu et al., 2002). Such gradients are much weaker for PM_{10} ($PM \leq 10$ μm) and $PM_{2.5}$ ($PM \leq 2.5$ μm; Goel and Kumar, 2016; Kumar and Goel, 2016). Stationary monitoring stations provide a general view of actual fluctuation in air pollutants to which inhabitants are exposed (Chen et al., 2016a, 2016b; Reche et al., 2011). Such monitoring networks only provide a partial insight in personal exposure since this differs greatly with activity, location and time spent on each activity (Bekö et al., 2015; Buonanno et al., 2013; Rivas et al., 2016). Therefore, exposure assessment during commuting deserves special attention.

The miniaturisation of air pollution monitors has allowed the proliferation of personal measurements studies in different transport microenvironments over the few last years (Table S1). The studies have shown that commuters come in contact with highly variable concentrations of atmospheric pollutants and face short-time extreme peak concentrations that results in significant contributions by commuting to

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the total daily exposure (12–32% of daily exposure; Dons et al., 2011; Rivas et al., 2016; Williams and Knibbs, 2016). Further, the exposure during commuting is highly affected by individual mode of transport. Comparison among studies is challenging owing to variability in the methods used for sampling and different conditions in each transport mode (such as ventilation rates and fuel type; Goel and Kumar, 2015a; Karanasiou et al., 2014; Kaur et al., 2007). Moreno et al. (2015a, 2015b) reported the following hierarchy for PNC in different transport microenvironments with data from various studies: urban background < underground < tram < walking in a suburban main road < walking and cycling in the city centre < bus. However, this hierarchy might differ for other pollutants. For example, the highest PM concentrations are expected to be found in the underground (Adams et al., 2001; Martins et al., 2016a). Concentrations of $PM_{2.5}$ were lower in buses than in cars in Barcelona (de Nazelle et al., 2012) and Arnhem (Zuurbier et al., 2010), but a reverse situation was reported in London (Adams et al., 2001) and Dublin (McNabola et al., 2008). Consequently, more studies, such as this work, are needed to identify the parameters affecting pollutant concentrations in different transport microenvironments.

The distribution of air pollutants has been found to be inequitable, with people living in most deprived areas generally suffering from higher concentrations of air pollutants (Fecht et al., 2015; Kingham et al., 2007; Wheeler and Ben-Shlomo, 2005; WHO, 2010; Yu and Stuart, 2016). The field of environmental justice has been notably explored in the U.S.A., where poorer people or ethnic minorities are exposed to higher air pollutant concentrations (Bullard, 2015; Hackbarth et al., 2011; Houston et al., 2004; Yu and Stuart, 2016). A smaller number of studies are available for European countries (Barceló et al., 2009; Moreno-Jiménez et al., 2016), sometimes with inconclusive results (Padilla et al., 2014; Wheeler and Ben-Shlomo, 2005) or reverse between socioeconomic status and air pollutants concentrations (Forastiere et al., 2007; Germani et al., 2014). In the UK, Fecht et al. (2015) found an association between PM_{10} concentrations and deprivation in England, with the most vulnerable groups encountering higher concentrations. However, in a between neighbourhood comparison, both Fecht et al. (2015) and Goodman et al. (2011) observed a nonlinear relationship as people in the higher social class would accept high levels of air pollution to take advantage of the benefits offered in city central areas. Jephcote and Chen (2012) found that children in lower social class households in Leicester tend to live in areas experiencing high levels of road transport emissions which were caused to a substantial extent by the private transport of affluent communities living in areas with low emissions.

Unlike available studies, this work assesses the inequalities in exposure to air pollutants during commuting using real-time personal measurements, thus providing a precise input of exposure concentrations. The main objective of this work is to determine if there are inequalities related to income deprivation in the exposure during commuting to different fractions of PM, BC and PNC in London. To this end, different routes in different transport modes were assessed, with the routes being typical commuting routes for inhabitants from 4 areas with different level of income deprivation (G_1 to G_4, representing from most to least deprived). Furthermore, we have assessed the differences between transport modes (car, underground and bus) and different daytime periods (morning and afternoon rush hour, midday non-rush hour) in order to identify the main drivers of exposure during commuting.

2. Methodology

2.1. Study area

The study was carried out in Greater London (Fig. S1), which has an area of 1572 km^2 and around 8 million inhabitants (Office for National Statistics, 2014), making it one of the largest cities in Europe. In March 2016, London counted 3.3 million registered vehicles (2098 veh km^{-2}), of which 2.8 million were cars (1809 cars km^{-2}; Department for Transport, 2016).

2.2. Route selection

2.2.1. Datasets used for the route selection

Two different datasets were used for the selection of the origin and destination of our routes. One was the 2015 Index of Multiple Deprivation (IMD; Department for Communities and Local Government, 2015), which is the official measure of relative deprivation for small areas in England. The index consists of a basket of indicators from seven domains (which measure different dimensions of deprivation) to produce an overall relative measure of deprivation. The second dataset was the 2011 Census Special Workplace Statistics (Census Support Flow Data, 2011), which includes commuting counts (location of usual residence and place of work by method of travel to work). Both datasets report statistics at a small area level, the Lower Layer Super Output Area (LSOA), which represent homogeneous neighbourhoods in terms of key demographic and socioeconomic characteristics.

From the seven domains of IMD (Smith et al., 2015), we selected the Income Deprivation Score to classify the LSOA areas within the Greater London into 4 different groups (G_1 to G_4, from most to least deprived, with G_1 and G_4 representing the 10% most and least deprived, respectively; Table S2). The Income Deprivation domain is not an individual measure of affluence but identifies aspects of income deprivation at the small area level and was selected to ease replication in other countries. The spatial distribution of both the Income Deprivation and the IMD score are presented in Supplementary Information Figs. S2 and S3, respectively. There is a strong correlation across London for both indexes, suggesting that similar results could be expected if IMD would be used instead.

2.2.2. Selection of the origins, the destination and the routes

We aimed to select typical commutes for areas of residence with different levels of income deprivation. We selected one workplace area that is a frequent destination for commutes from origins in all deprivation classes (area with highest employment density). The destination point was within the City of London (LSOA name: City of London 001F), which is the financial district (Fig. 1).

For the single destination, we selected four origins, one in each deprivation class (Fig. 1). For each income group (G_1–G_4), we calculated the average Euclidean distance that the inhabitants commute in order to get to the selected destination, according to the origin-destination information reported in the Census Support Flow Data (2011). An increasing distance was observed from the most to the least deprived (Table 1). Afterward, a random LSOA at the corresponding average distance from the destination was selected as the origin for each of the four income categories. The origin point of the route was then chosen within the selected LSOAs, obtaining 4 origin-destination (O-D) pairs.

According to the Census Support Flow Data (2011), across all groups, the dominant modes were car (private), underground and bus (Table 1) and, accordingly, these three transport modes were assessed in this work. For each of the 4 O-D pairs, we monitored the fastest route for each transport mode (Fig. 1). Table S2 indicates the specifications for each of the routes (main roads used for car, and bus and underground lines). The same underground lines in opposite directions were taken for G_1 and G_3 (Northern line, with part of G_1 also in Victoria line) and for G_2 and G_4 (District line).

2.3. Instrumentation and sampling design

This work has been focused on the assessment of the exposure to particulate pollutants. Gaseous pollutants are also an important threat to human health, but for practical reasons and because of their potential health effect we selected to monitor PM_1, $PM_{2.5}$, PM_{10}, BC and PNC. A GRIMM EDM 107 (GRIMM Technologies Inc.) aerosol spectrometer