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The impact of seating location on black carbon exposure in public transit buses: Implications for vulnerable groups

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ABSTRACT

This study assesses the differences in personal exposure to black carbon (BC) in the cabin of modern public buses in Stuttgart, Germany. We measured BC concentrations in four different seating locations, including priority seating locations, during rush hour and non-rush hour periods, and determined average exposures as well as the frequency of peak exposures. We hypothesize that the elderly and children (known to be more vulnerable to health impacts of air pollution) are exposed to higher concentrations as they are encouraged to make use of priority areas in proximity to doors in the middle of the bus, allowing for a greater flux of pollutants. We found no statistically significant difference in the mean BC concentrations between priority seating areas and other locations. However, a significant increase (+32%) in the frequency of BC peaks ('spikes') was observed in one priority seating area when compared to the back of the bus. Furthermore, we found that travelling during rush hour was associated with significantly higher average in-vehicle BC concentrations in all seating locations compared with off peak hours (1122 ng/m^3 or 38% higher), as well as a greater magnitude of the largest concentration spike of each trip 1295 ng/m^3 (38%). Further work may be necessary to refine most appropriate location for priority seating areas in buses and bus stops.

1. Introduction

Personal air pollution exposure in the transport microenvironment has received considerable attention over recent years (Rank et al., 2001, Boogaard et al., 2009, Dirks et al., 2012). In particular, pollution exposure while traveling using public transport can be up to 2–5 times higher than when at home or in urban background locations (Dons et al., 2012, Moreno et al., 2015). For illustration, one hour of travel in a 15-h day can contribute approximately a quarter of a person's daily average dose (Dons et al., 2012, Moreno et al., 2015). Importantly, many metropolitan areas are introducing policies to encourage the use of public transport for commuting (CIVITAS Initiative, 2013). Therefore, understanding pollution exposure in these environments is of importance (Lim et al., 2015). This is particularly true for public buses, as previous work has found that pollution exposure for bus passengers is considerably higher than for those travelling on trams and trains (Dons et al., 2012, Adams et al., 2001, Kaur et al., 2007).

One key pollutant associated with public transport is black carbon (BC). BC is a component of particulate matter (PM), specifically PM2.5 (particles $< 2.5\,\mu m$ in aerodynamic diameter), and is almost exclusively emitted through the incomplete combustion of diesel. Both short- and long-term exposure to PM, including PM2.5 and BC, have been found to be associated with both increases in health problems and mortality (Knibbs et al., 2011; Knol et al., 2009; Ostro, 2016; Pope et al., 2002). Monitoring subjects during a

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two-hour walk down a busy road, Shinharay et al. (2017) found that relatively short-term exposure to BC and ultrafine particles in particular can be associated with changes in lung function and signs of arterial stiffness (especially if a person suffers from pre-conditions, in this case Chronic Obstructive Pulmonary Disease (COPD)). In particular, significant changes in forces expiratory volume in the first second (FEV_1) was seen within one to two hours following exposure. Further pointing to the harmful effect of BC particles (BCP), Janssen et al. (2011) suggest that "the estimated increase in life expectancy associated with a hypothetical traffic abatement measure was four to nine times higher when expressed in BCP compared with the equivalent change in PM2.5 mass". As such, "BCP more closely resembles the harmful components in these air pollution mixtures than does general PM2.5" (Janssen et al., 2011). The BC level is therefore considered to be a useful measure of exposure to road traffic emissions and its associated adverse health effects.

Previous work on pollution exposure on buses has focused on a variety of possible determinants to explain exposure to BC (Kingham et al., 2011; Knibbs et al., 2011; Liu et al., 2015). Overall, the rush hour period has been established as a significant predictor of in-vehicle concentrations of BC compared to other times of the day (Kaur et al., 2007; Dons et al., 2012). In addition, pollutant concentrations (both BC and PM2.5) can vary significantly during a single trip; door openings at bus stops are associated with peak exposures over a matter of minutes for UFP and various other sizes of PM (Lim et al., 2015; Tsai et al., 2008; Zhu et al., 2010; Moreno et al., 2015). There is evidence that both increased exposures over short, in the order of hours (Sinharay et al., 2017), medium, in the order of a day (Anderson et al., 2012) and well as long term are associated with adverse effects on health. Little is known about the very short-term effects (on the order of minutes) of exposure on health although short-terms peaks can contribute significantly to the mean concentrations over longer periods.

Here we investigate the air pollution exposure of public transport passengers on modern buses in Stuttgart, Germany. Stuttgart faces the highest air pollution concentrations among all cities nationwide (Sueddeutsche Zeutunge, 2016; Office for Environmental Protection, 2016), with policies now in place to increase the use of public transport and reduce the use of private vehicles (SSB, 2014). Importantly, vulnerable groups, including the young and elderly, are often overrepresented in public transport, including buses, due to their relative low rates of private vehicle access (Langlois et al., 2016). These vulnerable passengers are often seated near doors, as they are encouraged to make use of these priority seating areas, and therefore could be exposed to higher pollutant concentrations compared to other bus passengers. This is critical, since these vulnerable passengers, including children, the elderly, diabetics, and asthmatics, are more likely to suffer from increased cardiovascular complications and reduced lung function when exposed to transport pollutants compared with the general population (Laumbach et al., 2010; Morgenstern et al., 2007, Weichenthal et al., 2008; Kim et al., 2004).

To date only limited studies have focused on seating location as a determinant of exposure to PM. Hill et al. (2015) and Rim et al. (2008) measured $PM_{2.5}$ and Ultra Fine Particle (UFP) counts in American school buses. They found that the influx of diesel fumes was generally related to the openings of the front door of the bus, resulting in higher average concentrations in the front of the bus compared to the middle section. A study on public buses, which have a different configuration compared to school buses, found that pollutant concentrations were around 2–7 times higher in the back of the bus than in the front (Vijayan and Kumar, 2010). Regardless of the outcomes, these studies show the importance of seating location on the exposures of those travelling by bus.

In this paper, we aim to fill a knowledge gap by investigating determinants of in-cabin BC concentrations on a modern public bus. We investigate several parameters of possible importance to the mean and peak BC exposures (of several minutes or less) in modern public buses including: seating location; rush hour; and door openings. Importantly, we specifically target the relative exposure of vulnerable groups, who are encouraged to make use of priority seating areas in the bus.

2. Methods and data

The study was conducted in Stuttgart (Germany) from 28th to 31st December 2015 between the times of 8:30AM to 7:30PM. A total of 36 trips were made, with each trip consisting of the same route through the city (Fig. 1). The route selected follows a main arterial road passing along a route frequently experiencing congested traffic conditions. In total, the route consists of 11 stops. The average (one-way) trip duration was around 15 min, with each individual trip duration subject to the extent of traffic congestion at the time of data collection. Bus doors do not always open at every stop, but only open when required by passengers.

To reduce variation in pollutant concentrations attributable to bus configuration, the study was limited to one bus model, the 2007 Mercedes Benz CapaCity O 530 GL, running on diesel (Daimler AG, 2016). In addition to diesel, these buses are fueled with AdBlue (urea waste) to reduce the amount of nitrogen oxide in the exhaust. The city of Stuttgart increasingly employs these hybrid buses to help minimize emissions and hence pollutant concentrations in the inner-city basin, making them representative of the buses operating in the city. Measurement locations used within the bus can be seen in Fig. 2, and were in the front, back, middle-door, and middle-window. The middle-door, and middle-window locations are the two priority areas for vulnerable passengers on this model of bus. The bus model is fitted with air conditioning options, and has an electric ventilator system on the roof at the back of the bus.

Four MicroAeth AE51 units (AethLabs, San Francisco, USA) were used to monitor BC concentration at 10 s intervals, with a measurement error of 100 ng/m^3 (AethLabs, 2016). The units were pre-calibrated, measuring near-identical concentrations of BC in a test setting. Therefore, no post hoc data adjustments were required. However, the units were rotated between the measurement locations each trip to avoid any systematic instrument bias that may have existed. Of the trips included, 17 were collected on the Monday, 10 on the Wednesday, and 9 on the Thursday. As this work was undertaken during a holiday period, the trips taken before 11:00 AM and after 4:00 PM were coded as rush hour while the remaining trips were coded as non-rush hour. Using this classification, 21 and 15 trips were taken during rush hour and non-rush hour, respectively.

To compare the impact of the predictors 'rush hour' and 'seating location' on the BC environment in the bus cabin, three analyses