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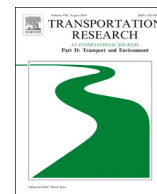
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The impact of seating location on black carbon exposure in public transit buses: Implications for vulnerable groups

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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/m³ or 38% higher), as well as a greater magnitude of the largest concentration spike of each trip 1295 ng/m³ (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 PM_{2.5} (particles < 2.5 µm in aerodynamic diameter), and is almost exclusively emitted through the incomplete combustion of diesel. Both short- and long-term exposure to PM, including PM_{2.5} 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 forced expiratory volume in the first second (FEV₁) 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 PM_{2.5} mass”. As such, “BCP more closely resembles the harmful components in these air pollution mixtures than does general PM_{2.5}” (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 PM_{2.5}) 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 (Shinharay 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-term 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 Zeitung, 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/m³ (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

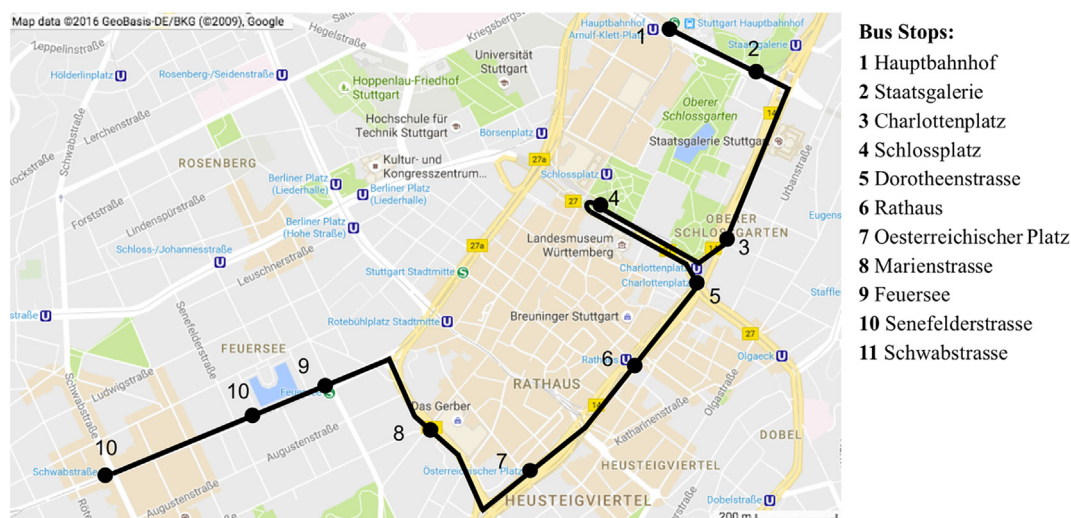


Fig. 1. Bus route and stops. The scale is visible in the bottom right corner of the figure.

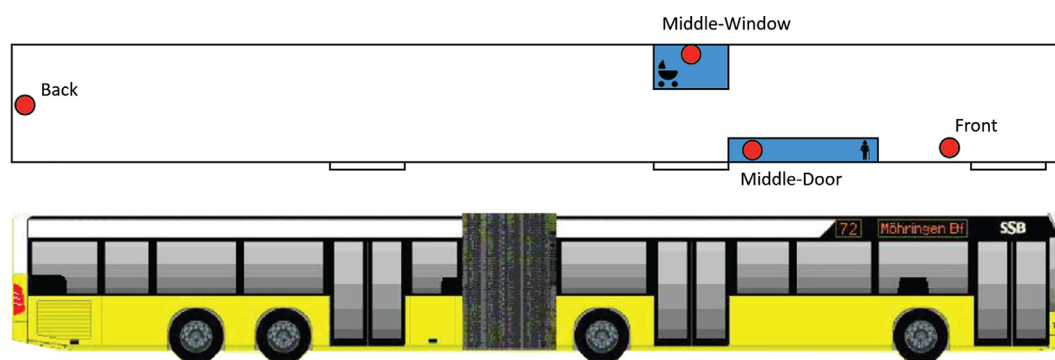


Fig. 2. Measurement locations inside the vehicle are indicated by the red circles. The priority seating areas are highlighted in blue.

were conducted: (i) comparisons of the mean BC concentrations, (ii) comparisons of the frequency of BC peaks, and (iii) comparisons of the magnitude of BC peaks.

Since the data are made up of instantaneous, time-series measurements that are not statistically independent, for the first analysis (mean BC concentrations), we averaged the BC concentrations per loop for each measurement device and compared the means. In the second analysis, we investigated the frequency of BC peaks, defined as peaks with concentrations above 300 ng/m^3 . Peak analysis was performed using the Matlab *findpeaks* script, specifying a minimum peak prominence above 300 ng/m^3 . Prominence is defined by 'how much a peak stands out due to its intrinsic height and location relative to other peaks' (see <https://nl.mathworks.com/help/signal/ref/findpeaks.html#buff2t6> for further information). For ranges of peak prominence between 150 and 1500 ng/m^3 findings discussed in the results section were robust, that is statistically significant. We hypothesise that this is reasonable since peaks lower than 150 ng/m^3 are close to measurement precision of the devices ($\pm 100 \text{ ng/m}^3$), and peaks larger than 1500 ng/m^3 were very unusual. Example peak analysis is shown in the results section in Fig. 3. In the third analysis, the same smoothed dataset and peak identification was used to calculate the mean peak magnitude for each location during each trip.

In addition, to understand the importance of door opening, the BC concentration before and after middle door openings at different bus stop locations were compared. The BC concentrations before and after door openings for 8 out of the 11 bus stops, shown in Fig. 2, were analysed. Two of the omitted bus stops were the start (Hauptbahnhof) and end (Schwabstrasse) of the bus route due to extended waiting times at these locations. The third omitted stop was Staatsgalerie since only the front door opened at this location. The differences were found by averaging the BC concentrations for 30 s before, and 30 s after opening of the middle door. The before and after concentrations were then analysed using a paired *t*-test for each location. There are some small, inset windows at the top of each larger window, which were open for some short periods. However, we were not able to find any significant influence of these openings on BC levels so these were ignored.

Statistical analyses were conducted using Matlab R2015b, with $\alpha \leq 0.05$. All data are reported as the mean $\pm$ standard error (SEM). All data were checked for normality and homogeneity of variance to meet the assumptions before statistical analysis. If assumptions were violated and p-values were close to α , this is highlighted in the text, as results need to be interpreted with caution. A two-way Analysis of Variance (ANOVA) was used for the first three analyses to investigate the impact of rush hour and seating

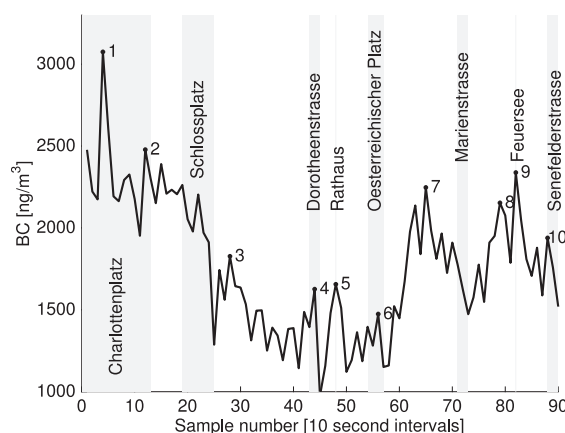


Fig. 3. The BC levels during a representative trip with door openings at the greatest number of stops. The BC levels plotted here are an average of the four locations on the bus. The grey regions show which bus stop location the doors were open for, and the duration of door opening. The round, numbered markers indicate the example peaks located in the data.

location, along with testing for interaction terms between the two. The impact of door-opening was done using a series of paired t-tests for each location.

3. Results

The BC levels for a representative trip are shown in Fig. 3. The grey shaded areas show the door openings and duration for each stop. The BC levels are calculated as averages of all four locations on the bus. In general, it is possible to see the high levels of BC on the bus while the bus waits with the doors open for a long duration (see Charlottenplatz in Fig. 3 as an example). Subsequently, a reduction in cabin BC levels is seen at Schlossplatz, located next to a park and on a road with restricted traffic (further discussed below). Finally, the general trend of a minimum level at or after Schlossplatz, is then followed by increasing BC levels as the bus continues through the city centre (see sample numbers 40 and onwards in Fig. 3 as an example).

3.1. Mean BC concentration

There was no significant interaction found between rush hour and seating location on mean BC concentrations (two-way ANOVA, $F_{3136} = 0.03$, $p = 0.99$). The mean BC concentrations in both of the middle seating locations were on average 160 ng/m^3 higher compared to the other seating locations, but differences were not found to be statistically significant (two-way ANOVA, $F_{3136} = 0.16$, $p = 0.92$). However, there was a significant increase in BC concentration during rush hours compared to non-rush hours (two-way ANOVA, $F_{1136} = 26.59$, $p < 0.001$). On average, rush hour concentrations of BC were 1122 ng/m^3 (38%) higher than during non-rush hours; further summary statistics are presented in Table 1.

3.2. Frequency of peaks

There was no significant interaction effect between rush hour and seating location on the frequency of BC peaks (two-way ANOVA, $F_{1136} = 1.27$, $p = 0.29$). However, the seating location did show a significant difference in the frequency of BC peaks (two-way ANOVA, $F_{1136} = 7.35$, $p < 0.001$). Post-hoc analysis revealed significant differences in the frequency of peaks between the back seat and the middle window seat (Tukey-Kramer $p < 0.05$). The number of peaks was 32% higher in the middle-window, priority

Table 1

Mean BC concentrations ($\pm$ SEM) during non-rush and rush hours for the four seating locations. All values are given in units of ng/m^3 along with the standard error of the mean, also in ng/m^3 . Different letters a and b indicate significant differences between groups (two-way-ANOVA, $p \leq 0.05$). For example, 'a' and 'b' here indicate that there is a significant difference between the average BC levels between rush, and non-rush hours.

Seating location	Non-rush [ng/m^3]	Rush [ng/m^3]	Average [ng/m^3]
Front	2830 ± 110	3995 ± 47	3542 ± 38
Middle-door	3013 ± 107	4180 ± 47	3726 ± 38
Middle-window	2983 ± 110	4137 ± 49	3688 ± 39
Back	2948 ± 118	3949 ± 46	3560 ± 38
Average	2943 ± 27 a	4065 ± 12 b	

Table 2

Frequency of BC peaks ($\pm$ SEM) during non-rush and rush hours for the four seating locations. All values are given in the number of peaks along with the standard error of the mean, also in the number of peaks. Different letters a and b indicate significant differences between groups (two-way-ANOVA, $p \leq 0.05$). For example, a and b here refer to significant differences in the frequency of BC peaks between the middle-window seat and all other seating positions.

Seating location	Non-rush [# of peaks]	Rush [# of peaks]	Average [# of peaks]
Front	13.14 $\pm$ 0.32	11.50 $\pm$ 0.17	12.13 $\pm$ 0.11 a
Middle-door	11.64 $\pm$ 0.25	11.09 $\pm$ 0.15	11.31 $\pm$ 0.09 a
Middle-window	16.79 $\pm$ 0.29	13.82 $\pm$ 0.22	14.97 $\pm$ 0.14 b
Back	11.14 $\pm$ 0.24	11.77 $\pm$ 0.19	11.53 $\pm$ 0.11 a
Average	13.18 $\pm$ 0.08	12.05 $\pm$ 0.05	

seating area than at the back of the cabin, approximately below the roof ventilator. There were no further statistically significant differences. Rush hour showed some, weak indication of the frequency of peaks (two-way ANOVA, $F_{1136} = 2.77$, $p < 0.098$). Summary statistics are presented in Table 2.

3.3. Magnitude of peaks

There was no statistically significant interactive effect of rush hour and seating location on the peak magnitude of BC concentration (two-way ANOVA, $F_{3136} = 0.04$, $p = 0.99$). In addition, the seating location was not statistically significant with respect to the peak magnitude (two-way ANOVA, $F_{3136} = 0.32$, $p = 0.81$). During rush hour, the magnitude of the largest peak event for each trip was significantly higher compared to non-rush hours (two-way ANOVA, $F_{1136} = 27.03$, $p < 0.001$). On average, peak events were 1295 ng/m³ (38%) higher during rush hour than during non-rush hours; further summary statistics are presented in Table 3.

3.4. Influence of door opening

While there are indications that mean differences do arise at some bus stops, i.e. that concentrations increase after door opening, these differences are not found to be statistically significant (Table 4). Only Schlossplatz shows a statistically significant change in BC concentration before and after door opening in the form of a reduction of 357 ng/m³. Schlossplatz is the only stop on the route not accessible to general traffic, and adjacent to a park (see Fig. 1).

4. Discussion

In this study, we found that the number of BC peak events during a bus trip in Stuttgart was significantly higher (on average 32%) in a priority seating location in the middle of the cabin than at the back of the cabin. We also found that the mean BC concentration for trips conducted during rush hour were significantly higher (on average, 1122 ng/m³ higher) than those conducted during off-peak periods. This is consistent with the findings of Kaur et al. (2007) and Dons et al. (2012). Not only were average BC concentration higher during rush hour periods, but the peak concentrations observed during each trip were over twice as high during the peak compared to non-peak periods. Also, the magnitudes of the peaks were 38% higher during rush hour periods.

Although we saw some variation between seating location and BC concentrations (in both the mean and peak measurements), we did not find any statistically significant dependence. Interestingly, mean BC concentrations (see Table 1) were similar in the front and back of the bus during rush hour and slightly lower compared to the middle of the bus. Ventilation could have been higher in these locations as the air intake was located in the front of the CapaCity bus, and the rear was equipped with an electric roof ventilator (Daimler AG, 2016). Thus, although the front of the bus was a pollutant entry point due to door openings, the location of ventilation systems might have facilitated the quick dispersion of pollutants. This correspondence of levels in the front and back of the bus differs

Table 3

Magnitude of BC peak concentrations ($\pm$ SEM) during non-rush and rush hours for the four seating locations. All values are given in units of ng/m³ along with the standard error of the mean, also in ng/m³. Different letters a and b indicate significant differences between groups (two-way-ANOVA, $p \leq 0.05$). For example, a and b here indicate that the magnitude of non-rush, and rush our peaks are statistically different.

Seating location	Non-rush [ng/m ³]	Rush [ng/m ³]	Average [ng/m ³]
Front	3163 $\pm$ 106	4458 $\pm$ 57	3955 $\pm$ 41
Middle-door	3466 $\pm$ 116	4709 $\pm$ 58	4225 $\pm$ 42
Middle-window	3399 $\pm$ 117	4836 $\pm$ 64	4277 $\pm$ 46
Back	3468 $\pm$ 129	4673 $\pm$ 61	4204 $\pm$ 45
Average	3374 $\pm$ 29 a	4669 $\pm$ 15 b	

Table 4

Statistical relationships for middle door opening locations (paired student *t*-test). The mean difference ($\pm$ SEM) is the average difference in BC concentration in the middle seat location averaged 30 s before, and averaged 30 s after door opening.

Bus stop location	N	Mean difference [ng/m ³]	P
Charlottenplatz	10	405 $\pm$ 105	0.59
Schlossplatz	25	−357 $\pm$ 11	< 0.001
Dorotheenstrasse	7	−20 $\pm$ 79	0.32
Rathaus	17	239 $\pm$ 28	0.13
Oesterreichischerplatz	25	11 $\pm$ 15	0.11
Marienstrasse	22	211 $\pm$ 23	0.11
Feuersee	22	231 $\pm$ 28	0.076
Senefelderstrasse	10	−18 $\pm$ 53	0.97

from other studies which, as described above, found significant differences between the two locations (for example [Vijayan and Kumar \(2010\)](#) and [Hill et al. \(2015\)](#)). Possible reasons for this is that previous studies have generally focused on older buses with less effective ventilation systems than the bus models investigated here. Additionally, there has been discussion in the literature regarding pollution arising from the bus itself, and there may be spatial differences in this self-pollution through the bus. In this work, we did not measure reliable levels of this pollution as the bus was always running throughout the route, even when in between trips. Levels for soot have been found to be 46% higher in diesel buses compared to electric buses ([Zuurbier et al., 2010](#)), similar to those found in other studies, albeit for older school buses in America ([Adar et al., 2007](#), [Behrentz et al., 2004](#)). However, we did find that the frequency of events experienced by the middle-window location was significantly higher than the back-seat location. This may be explained by the proximity of this location to the large, middle door entrance. Our results suggest that once the doors have closed, the pollutants become well mixed within the cabin.

Finally, we investigated BC concentrations 30 s before and 30 s after door openings and found statistically significant differences (reductions in concentrations) at the Schlossplatz bus stop. This difference may have been particularly pronounced as it was the only stop not accessible to traffic and located in an open space within a park. While it is not possible to come to any firm conclusions on the basis of evidence from a single bus stop location, the findings nevertheless are consistent with those of [Tallis et al. \(2011\)](#) who identified green buffer-zones as being highly effective at reducing localized pollutant concentrations. [Lim et al. \(2015\)](#) highlight the detrimental impact of bus stop located in proximity to intersections. There is also some evidence to suggest that moving at least one stop away from the road to a less trafficked greener area can be expected to allow clean air to enter the bus cabin and reduce pollutant concentrations inside the bus. During the measurement period, bus driver changes occurred at a bus stop on a busier road (Charlottenplatz). Relocating this switch of drivers to the Schlossplatz bus stop could naturally introduce a longer stop at this location and could facilitate a better air exchange.

5. Conclusions

The results of this study suggest that the average BC exposure of passengers is not affected by seating location in the front, middle or at the back of the bus. However, the priority seating area in the middle of the bus is associated with a higher likelihood of experiencing a peak in concentration when compared to seating at the back of the bus. Secondly, those traveling during rush hour are subject to both higher mean concentrations as well as higher magnitudes and frequencies of BC peaks. Lastly, this study shows that the location of bus stops can play a significant role in reducing in-cabin concentrations.

It is important to note that the measurements were taken during vacation periods. Thus, differences in concentrations between rush and non-rush periods could be expected to be more pronounced during regular working time. Also, differences in bus patronage could also have affected bus ventilation and pollutant dispersion.

There is some evidence to suggest that bus route planning should consider moving one bus stop at least to one in proximity to urban greenery to allow for more effective pollutant outflow. Clear and reliable identification of the determinants of heightened in-vehicle concentrations could ensure that the shift to public transport is not only beneficial to the environment, but also that exposure of passengers to pollutants inside public transit buses is limited in order to avoid potential adverse health effects.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trd.2018.04.009>.

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