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Personal exposure to air pollutants in a Bus Rapid Transit System: Impact of fleet age and emission standard

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ABSTRACT

This work documents the extremely high concentrations of fine aerosol particles ($PM_{2.5}$), equivalent black carbon (eBC) and carbon monoxide (CO) experienced by commuters in one of the world largest Bus Rapid Transit (BRT) systems, located in Bogotá, Colombia. A strong relationship between vehicle emissions standard and in-vehicle concentrations was established. Extensive measurements of $PM_{2.5}$, eBC, and CO were carried out inside the system buses and stations. Measurements were performed during eleven months covering all the system lanes and a significant fraction of the bus fleet and stations. Based on the observed in-bus and in-station concentrations, travel times, and urban ambient levels, the contribution of a typical round trip in the BRT system to the daily inhaled dose was estimated to be 60% for $PM_{2.5}$, and between 79% and 90% for eBC. The mean $PM_{2.5}$ dose inhaled by commuters in a typical round trip in the system is 1.2 times the dose a subject would inhale over 24 h exposed to WHO guideline of 25 $\mu g\ m^{-3}$. In 52 out of 180 buses sampled the mean in-cabin concentration of *e*BC was in excess of 100 $\mu g\ m^{-3}$. Measurements show that mean ratio of in-bus to urban ambient concentration is 8:1 for $PM_{2.5}$ and 4:1 for CO. These ratios were observed to be much larger when traveling inside the older fraction of the BRT fleet, reaching 11:1 and 7:1 for $PM_{2.5}$ and CO respectively. These older buses consist exclusively of Euro II and Euro III nominal emission standard vehicles. Average exposure levels inside Euro II and III buses was twice as large as those measured inside vehicles with stricter emission standards, Euro IV or superior. Overall, the measurements suggest that the entrainment of polluted pockets of air to the semi enclosed micro-environments in the system, namely, buses and stations, explains the extreme observed exposure concentrations. Measurements inside an underground bus-station where traffic is restricted to only BRT buses, and on-board a zero emission fully electric BRT bus suggested most of the pollution in the system comes from entrainment of the exhaust of the diesel-powered BRT buses. The significantly lower exposure and inhaled dose of $PM_{2.5}$, eBC, and CO observed for commuters in newer vehicles suggests that a fleet renewal could have a disproportionately large impact on reducing population exposure to air pollutants. The extent of the reduction in exposure and inhaled dose through fleet renewal is proportional to the gradient of in-bus to urban ambient air pollution levels.

1. Introduction

Exposure to air pollutants has been extensively linked with negative health impacts (e.g., Pope III et al., 1991; Dockery et al., 1993; Samet et al., 2000; Brook et al., 2010; Dysart et al., 2014). Air pollution is thought to cause 17% of all non-communicable disease deaths between the ages of 30 and 70 (Krzyżanowski et al., 2005) and is the second largest risk factor after tobacco. Air pollution is estimated to have caused seven million premature deaths worldwide (Krzyżanowski et al., 2005). Urban commuters are of special interest, since their frequent proximity to pollutant sources implies repeated exposure to peak concentrations (Gulliver and Briggs, 2004; Kaur et al., 2007), which is thought to have substantial deleterious health effects (e.g., Krzyżanowski et al., 2005; Michaels and Kleinman, 2000). Activities related to daily commute are known to contribute significantly to personal exposure and dose of combustion related air pollutants. For instance, commuters in Brisbane (Williams and Knibbs, 2016) and The Flemish Region (Dons et al., 2012), spend approximately 6% and 9.8%

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of their day in traffic respectively, but commuting can account for around 30% and 32% of the daily equivalent black carbon (eBC) inhaled dose, respectively. Similar results have also been obtained for fine particles ($PM_{2.5}$) (e.g., de Nazelle et al., 2012), and carbon monoxide (CO) (e.g., Fernandez-Bremauntz and Ashmore, 1995).

Many studies have shown that travelers inside different types of vehicles are exposed to higher levels of particulates and other pollutants than users of other modes (e.g., Berghmans et al., 2009; Boogaard et al., 2009; Panis et al., 2010; Zuurbier et al., 2010; Cole-Hunter et al., 2012; Huang et al., 2012; Both et al., 2013; Kingham et al., 2013; Do et al., 2014; Suarez et al., 2014; Hankey and Marshall, 2015; Ramos et al., 2015; Cepeda et al., 2016; Jeong et al., 2017; Morales Betancourt et al., 2017). Poor air quality levels in micro environments associated with mass transit systems can have a large impact on population exposure to air pollutants, given their ridership and travel times (Rivas et al., 2017). Among mass transit alternatives, Bus Rapid Transit Systems (BRT) have shown the fastest growth rate worldwide. It is estimated that BRT systems around the world transport nearly 32 million people per day in 164 cities in every continent. Some 59 systems have been built since 2011, 55 cities are currently expanding their systems, and there are 121 more BRT systems in construction or in planning (BRT, 2018). Many of those BRT systems are either located or being built in cities in emerging economies, which often have less stringent emission standards, host aged vehicle fleets, and commuters endure longer travel times due to mobility challenges, which may imply higher inhaled dose of air pollutants during commute (Moraes and Schwanen, 2015; Goel et al., 2015).

The in-cabin concentration of air pollutants in public transport buses or other motorized modes of transport varies widely according to many factors, including the use of air conditioning, vehicle age and emission standard (Dekoninck and Int Panis, 2017), self-pollution (Marshall and Behrentz, 2005), as well as contributions from surrounding vehicles (Kingham et al., 2013; Zuurbier et al., 2010). The individual contribution of those factors is uncertain and may vary widely for different situations. Some studies have focused on understanding these factors through the development of statistical or physical models (Dekoninck and Int Panis, 2017). Furthermore, the in-cabin to ambient concentration ratio is affected by several environmental factors. For instance, high in-bus concentration of air pollutants are often reported in Asian mega-cities (Chan et al., 2002; Both et al., 2013; Goel et al., 2015; Yang et al., 2015). Some of those cities, however, also face severe air quality challenges. Despite the extremely high concentration of $PM_{2.5}$ reported inside urban buses in Delhi, the in-bus to ambient concentration ratio is close to 1. This implies a relatively small gradient of air pollution levels inside the transport micro-environment when compared to ambient levels. Deteriorated air quality levels have also been reported inside the public transport environments in Latin American cities, however, comparatively fewer studies on personal exposure have been conducted in this region where fuel quality and less stringent emission standards might contribute to high exposures. Some studies have been performed in Mexico (Fernandez-Bremauntz and Ashmore, 1995; Vallejo et al., 2004), Peru (Han et al., 2005) and more recently in Chile (Suarez et al., 2014), Colombia (Morales Betancourt et al., 2017), and Brazil (Targino et al., 2016). However ambient air pollution levels in Latin American cities are typically moderate. Personal exposure to $PM_{2.5}$ in Santiago de Chile's BRT system was found to be similar to the concentrations reported at the fixed monitoring sites, with mean in-cabin commuter exposure of 65 $\mu g\ m^{-3}$ compared to 54.5 $\mu g\ m^{-3}$ reported at the fixed monitoring site during commute hours. Those results imply a relatively low in-cabin to ambient concentration ratio.

In studies carried out in other regions of the world, low to moderate in-bus exposure to $PM_{2.5}$ ($\leq 30\ \mu g\ m^{-3}$) has been reported (Asmi et al., 2009; Rivas et al., 2017; Tan et al., 2017; de Nazelle et al., 2012). However, in most cases, the cities where the studies were done exhibit also low to moderate ambient concentrations, with in-bus to ambient concentration ratio of $PM_{2.5}$ between 1.1 and 1.2. Studies in European cities suggest a slightly larger in-bus to urban ambient ratio compared to Delhi, of around 1.3. However, background air pollution levels are much lower for those locations. In contrast to these moderate exposure levels, a study performed in Bogotá found an alarming 9 to 1 in-bus to urban-ambient concentration for a specific route segment studied in Bogotá's BRT system, called Transmilenio, (Morales Betancourt et al., 2017). The study also found the BRT buses to be the micro environment with the largest $PM_{2.5}$, eBC, and ultra-fine particle concentrations across all the modes considered, with levels roughly 6 times larger than those experienced by pedestrians in the vicinity of the BRT lanes. That study, however, was limited to one of the ten lines of the city's BRT system. In addition there is a large variability in the bus fleet regarding vehicle age and emission standard as the system buses have progressively entered in operation at different stages over a span of 16 years. This variability was not accounted for in Morales Betancourt et al. (2017).

In this study we aim to characterize the exposure in the BRT system in a manner that is representative of the entire system, and to identify a quantitative relationships between vehicle-specific characteristics and the in-cabin level of exposure experienced by commuters. We performed extensive sampling of $PM_{2.5}$, eBC, and CO concentration inside the BRT system, quantifying exposure to particulate and gas phase pollutants for commuters. We crossed these exposure measurements against bus-specific information regarding manufacturer, vehicle age, vehicle kilometers traveled, and nominal emission standard of the vehicle, to determine potential impacts of the fleet characteristics on commuters' exposure. These impacts are relevant because Bogotá BRT system is one of the world's largest, with an estimated 701.5 million passengers transported in 2016, and a current workday ridership close to 2.4 million in 2017.

2. Materials and methods

2.1. Study area and data collection

We measured air pollutant concentrations in an extensive portion of Bogotá BRT system (Transmilenio). The sampling covered the entire 113 km of dedicated BRT lanes. The system started operation at the end of 2000, serving 116.6 million passengers in 2001. Its demand has grown by about 35.5 million passengers every year reaching 2.4 million daily trips in 2017. This is one of the largest BRT systems in the world, with 149 bus stations and a fleet of 2005 buses (75% articulated, 15% bi-articulated, 10% single-cabin buses). There is one fully electric BRT bus in service. Single-cabin buses are hybrid (diesel-electric) with 9.4 L engines. The remaining articulated and bi-articulated buses are all diesel-powered, with engines displacements of up to 14 L (bi-articulated buses). The fleet is considerably old, with 37% of the vehicles between 10 and 17 years of operation as of 2017. The BRT system has often been used as a model for the implementation of similar systems in other cities (Mejía-Dugand et al., 2013). Briefly, in most of its segments it uses exclusive lanes parallel to mixed traffic, which is mostly gasoline powered. A detailed description of the configuration of the Transmilenio system, its bus lanes, the traffic composition in adjacent lanes can be found elsewhere (Hidalgo et al., 2013; Morales Betancourt et al., 2017).

During our sampling campaign we performed round trips in the mass transit system while carrying a set of portable sampling devices for $PM_{2.5}$, *e*BC, CO, and physical activity. Particle number size distributions were measured on some occasions using an optical particle sizer. The trips started from the city center towards one of the 9 system terminal stations. Sampling duration was designed to be representative of a typical round-way trip, characterized by an average duration of 140–160 min. Measurements were performed between February and December of 2017, exclusively on weekdays morning rush hour, between 7am and 10am. All instruments were carefully synchronized. The

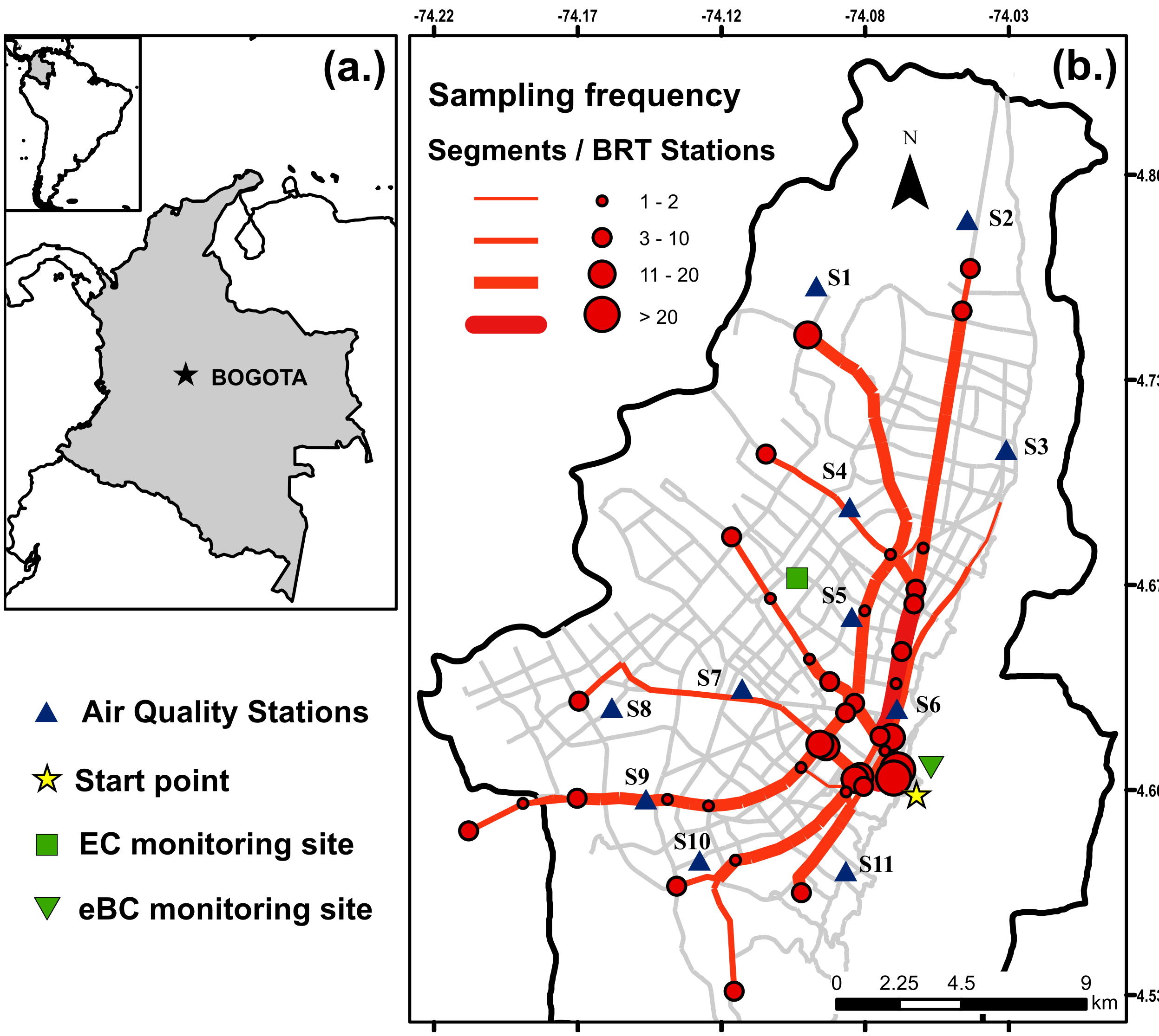

Fig. 1. (a.) Geographic location of the city of Bogotá. (b.) Spatial distribution of the sampling frequency of the BRT system. Sampling frequency of bus stations (circles) and BRT lines (line segments) is shown. The thickness of the line segments and size of the circles is related to the sampling frequency. The starting point for the trips is marked with a star. Triangles show the location of the 11 fixed monitoring sites of the local air quality network used in this study to determine urban ambient concentration. All stations reported $PM_{2.5}$ for the study period. Stations S3 to S5 and S7 to S9 reported CO during the same period.

sample inlets were located in the breathing zone of the individual carrying the devices. Detailed schedule of the field campaign and instruments available for each sample can be found in Supplementary Material.

2.2. $PM_{2.5}$, eBC and CO exposure measurements

Concentration measurements of $PM_{2.5}$, *e*BC, aerosol particle size distribution, and CO were performed in various micro-environments associated with the BRT system. These micro-environments included buses, stations, as well as walking trips from the starting point to the bus-stations. Physical activity was measured using accelerometers. The instrumentation and methods used in this study follow closely those of similar studies (Morales Betancourt et al., 2017), and are only briefly described here. Laser scattering based instruments (DustTrak 8520 and DustTrack DRX 8533, TSI Inc. MN, USA) were utilized to determine continuous $PM_{2.5}$ concentration. A set of Personal Environmental Monitors (PEMs) (SKC Inc. PA, USA) consisting of a single-stage $PM_{2.5}$ impactor and 37 mm PTFE collection filter were used for gravimetric determination of $PM_{2.5}$. The PEM sampling flow rate for a 2.5 μm cut diameter is 4 LPM, which was carefully calibrated before and after each sampling day. PEMs were utilized as an independent method to ensure the overall accuracy of the optical $PM_{2.5}$ measurement. PEMs were carried in 44 out of 46 sampling days, typically in pairs. Due to the relatively short sampling times, uncertainties in the filter weights was an issue in some days due to small collected mass. To overcome this issue, only samples for which duplicate filter samples were within 30% of each other were used for comparison to the photometric sensors. DustTrak 8520 showed a 5.7% ± 28% mean bias relative to the filter samples, and the DRX-8533 model a 11.5% ± 17.9% relative mean bias, implying that both devices slightly overestimated gravimetric filter data. Aerosol particle number size distributions were measured on a limited number of occasions using an optical particle sizer (OPS-3330, TSI Inc. MN, USA). The OPS is a single-particle detection device that counts and classifies particles into 16 size bins in the range of 0.3 μm to 10 μm optical particle diameter. *e*BC data was collected with portable Aethalometers (MicroAeth AE51, AethLabs, CA, USA) operated at a standard flow rate of $50 cm^3 min^{-1}$ and a sampling interval of 10 s. Following the guidelines of Petzold et al. (2013), we refer to the concentrations of Black Carbon derived from the Aethalometer as

Equivalent Black Carbon. The raw *e*BC data was corrected for filter loading effects which are known to affect Aethalometers (e.g., Virkkula et al., 2007, 2015). We adapted the correction procedure of Drinovec et al. (2015) to the AE51. The method is based on measuring *e*BC in the same environment at different flow rates to obtain different filter loading rates. The details of our implementation of the correction method can be found in the Supplementary Material. The mean loading correction parameter found was $k = 0.005$, consistent with findings in other studies (Cheng and Lin, 2013). Since we are measuring exclusively in near-road environments, heavily affected by fresh primary combustion of fossil fuels, we do not considered any seasonal variations on the loading correction factor. New filters were used for each sampling day. However, due to the extreme in-cabin concentrations encountered, even with the AE51 operated at its minimum flow rate, filters occasionally reached an attenuation of 100 or more even after just 30 min of sampling. Only data with a maximum attenuation of 140 is reported in this study. Concentrations of CO were measured with electro-chemical cell sensors (DeltaOhm, P37AB147 SICRAM probes), with a reported accuracy of ± 3 ppm for CO at a temporal resolution of 15 s. Temperature and relative humidity were also recorded at the same frequency.

Commuter exposure measurements were performed during an elven-month period. During this long sampling period, day-to-day variations in the urban ambient air pollution levels could be significant and therefore should be accounted for in the analysis. Urban ambient levels of $PM_{2.5}$ and CO were determined with hourly data from the 11 air quality monitoring stations in Bogotá. All monitoring sites reported $PM_{2.5}$ but only six reported CO for the full sampling period (Fig. 1). Monthly mean $PM_{2.5}$ and CO concentrations for 2017 exhibited the typical observed annual cycle with higher values for February, March, and November, and the lowest values observed during June, July, and August (Fig. 2). Locations of the air quality (AQ) monitoring sites in relation to the BRT system layout are shown in Fig. 1. The AQ sites are located in the vicinity of several BRT lines and stations. Six of the sites are located less than 1 km away from a BRT station, 9 sites within 1.5 km of a BRT station, and all of the sites are located less than 2.5 km away from the closest BRT station. Detailed description of the type of AQ station and their locations is included in the Supplementary Material. Two methods were used to characterize a representative urban ambient concentration relevant to compare against the commuter exposure data. First method was to compute the mean 7am–10am $PM_{2.5}$ and CO concentration from the sites, representing rush-hour urban ambient levels. Rush-hour levels are considerably higher than daily mean values, as is typical in most cities. The second method consisted on computing an inverse distance weighting concentration using the AQ site data (also rush-hour mean) for each of the

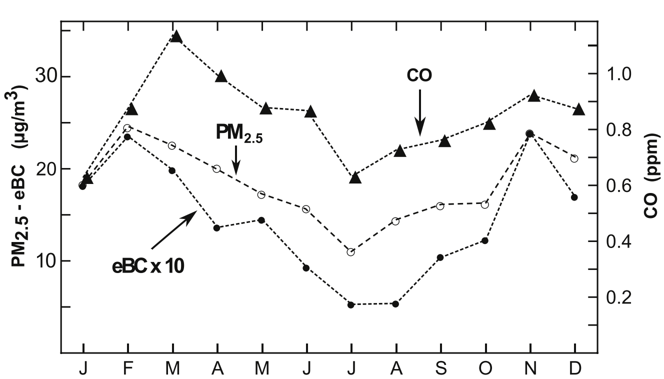

Fig. 2. Monthly mean $PM_{2.5}$ (open circles), CO (filled triangles), and *e*BC (filled circles) during 2017 in Bogotá. $PM_{2.5}$ and CO concentrations were obtained from the fixed air quality monitoring sites in the city. *e*BC concentrations were measured with an AE33 Aetahlometer at an urban-background site located in the eastern margin of the city (see Fig. 1).

segments and BRT stations sampled on each day. In this way, more wight was given to AQ stations that are closer to the exposure measurement locations, and less weight to those far away.

Accelerometers (Actigraph GT3X+, Ft. Walton, FL.) placed in the hips of the subjects were used to measure physical activity level simultaneously with air pollutant concentration data. The GT3X + measures acceleration in three axis, at a frequency of 30Hz. The acceleration event counts have been shown to correlate with Metabolic Equivalence Units (METs) (Freedson et al., 1998) and ventilation rate (Kawahara et al., 2011). All measured variables were synchronized at a 10 s time base.

Each BRT bus boarded was individually identified through its license plate. Information associated with each sampled bus was later gathered from a database of the public transport agency (*Transmilenio*, personal communication). This database included vehicle date of initial entry into operation, vehicle nominal emission standard, vehicle kilometers traveled (VKT), engine manufacturer, engine displacement, among other. None of the buses sampled had particulate emission control systems. Since the study is focused on the characterization of the typical exposure experienced in-cabin of the BRT buses the ventilation status on each bus was not controlled for. However, temperatures in the city remain stable throughout the year, with minimum and maximum daily temperatures on the range of 10 °C–20 °C throughout the year. Because of the weather stability and mild temperatures, AC use is not prevalent and is not expected to have changed significantly during the sampling period.

In-station sampling also took place as part of the trips performed. Stations were sampled during the waiting times associated with boarding a given bus route on a specific bus station. The three types of bus stations in the system were sampled, namely, regular stations, terminal stations, and one underground station. Regular stations (139 out of 149) are semi-enclosed spaces, located in the middle of the BRT lanes. This stations are equipped with sliding doors on both sides for boarding the buses. Typically these stations have more than one bus docking position along the longitudinal direction on each side. The common configuration is to have at least three docking stations on each side. A unique characteristic of the BRT system is that at the stations there are two exclusive lanes per direction of traffic. This is designed to allow other buses to overtake those that are picking up passengers at that bus station. Therefore, the regular stations are separated from the mixed traffic lanes by at least two exclusive BRT lanes in each direction of traffic. Terminal stations have a different topology to that of the regular stations. The terminal stations (9 out of 149) are open spaces, with wide platforms on which passengers wait to board/deboard the BRT-buses. These stations do not have sliding doors separating the passengers from the BRT buses. The system also has one underground station which consist of a 450 m long tunnel for the BRT buses. Passenger platforms in the underground station are 150 m long, located in the middle section of the tunnel and in-between the BRT lanes. The passenger platform is separated from the BRT buses by sliding doors similar to those of regular stations (see Supplementary Material). Careful notes were taken during the data collection process, registering the exact times of arrival to a BRT station, exact time of BRT bus boarding and deboarding. This methodology allowed for real time identification of micro-environment, precise measurement of in-bus travel time, as well as in-station waiting times. Further detailed information about the system can be found elsewhere (Hidalgo et al., 2013).

2.3. Urban ambient *e*BC estimation

Although *e*BC is not measured by the air quality network stations, we estimated upper and lower limits to the contribution of *e*BC to urban ambient $PM_{2.5}$ based on two different sources. Firstly, a year-long study performed in 2015–2016 quantified Elemental Carbon (EC) in PM_{10} samples collected at an urban background location in the city of Bogotá

(Ramírez et al., 2018). Annual mean EC concentration was 3.25 ± 1.59 $\mu g\,m^{-3}$, corresponding to 8.7% of PM_{10}. Maximum EC daily concentration was 11.3 $\mu g\,m^{-3}$ across 308 daily measurements. No substantial seasonal pattern was observed in the EC concentration. To infer the contribution of EC to $PM_{2.5}$ we used the $PM_{2.5}$ to PM_{10} ratio historically observed in the long-term datasets from the fixed monitoring sites. This ratio is close to 0.5 for the city of Bogotá, meaning the coarse and the fine fractions contribute equally to PM_{10}. Given that EC is originated in combustion, we assume that all the EC is likely in the fine fraction. Therefore, with this assumptions, the contribution of EC to $PM_{2.5}$ should be twice as large as its contribution to PM_{10}. Although EC and eBC are different estimates of carbonaceous aerosols, EC is often quantitatively represented by eBC due to its strong light-absorbing properties. With those assumptions urban ambient eBC/$PM_{2.5}$ is ~ 17.5%. This limit is likely an overestimation and it is therefore regarded as an upper limit to eBC/$PM_{2.5}$ ratio in the city. Although high, similar levels have been reported in Indonesian cities (Santoso et al., 2013). A second data source was utilized to estimate a lower limit on the eBC/$PM_{2.5}$ ratio. Bench Aethalometer data (AE-33, Magee Scientific, CA, USA) collected during the entire year of 2017 in a hill-top station a few hundred meters away from the city center was used to directly establish the seasonality of eBC. The site is located in the clean sector of the city. Concentrations at this site can be considered representative of urban background. eBC concentration at this site follows the same seasonality as $PM_{2.5}$ (Fig. 2). The ratio of the AE-33 monthly mean data to the $PM_{2.5}$ measured at the AQ monitoring sites has a maximum value of 10% for February and November, and a minimum value of 5.0% during July and August. The annual mean eBC/$PM_{2.5}$ is 8%. Due to the location of the site far from the traffic sources, this value likely an underestimation of eBC, and is used as a lower-limit estimate of the actual urban ambient ratio. Both limits are utilized in Section 3.2 to estimate the eBC exposure outside of the BRT system. The measurement sites for both data sets used are shown in Fig. 1.

3. Results and discussion

3.1. Exposure concentrations

The sampling campaign encompassed a total of 136 h, of which 63 h were in-bus sampling, 34 h were in-station sampling, and 16 h of sampling in the short walks to or from stations. Another 22 h of data are indoors sampling, mostly spent inside the University which was the starting point for all sampling days. The in-bus sampling covered a total distance of 802.2 km traveled in the system buses. Measurements were performed in 180 individual BRT buses (of a total fleet of 2150) and 39 different stations. A detailed summary of the full campaign can be found in the Supplementary Material. The average exposure concentration observed in the system buses and stations is shown in Fig. 3. The spatial distribution of the observed concentrations shows that almost all system branches and stations have median $PM_{2.5}$ concentrations higher than 100 $\mu g\,m^{-3}$, with some critical branches and stations having even higher levels. A similar situation is observed for eBC and CO. Fig. 3 suggests that some branches of the system and its stations have higher than average concentrations. This is discussed in Section 3.3.

Concentrations of $PM_{2.5}$, eBC, and CO were highly correlated and typically increase concurrently when sampling is performed inside the BRT buses. An example of data taken on a typical sampling day can be seen in Fig. 4. Both BRT buses sampled on that specific date had over 16 years of operation and had traveled over 1.3 million km. Despite the extremely high concentrations recorded in that sampling day, those are not among the highest concentrations observed during the campaign. Average $PM_{2.5}$ concentration in *Bus 1* and *Bus 2* of Fig. 4 ranks them 38th and 23rd respectively out of 180 buses sampled. For the data of Fig. 4 $PM_{2.5}$, eBC, and CO are highly correlated ($\rho_{PM,eBC} = 0.85$, $\rho_{PM,CO} = 0.88$, $\rho_{eBC,CO} = 0.83$). The high correlation with CO, which was observed for every single measurement performed in the system, suggests combustion sources are indeed dominant, while the strong correlation with eBC further suggests the sources are rich in EC emissions. The time series of in-bus concentrations are characterized by spikes corresponding to episodes of entrainment of polluted air. Such concentration spikes have been associated in the literature with low-speed travel and passengers boarding at bus stops (Lim et al., 2015). A shift in the particle size distribution is observed when measurements are performed inside the BRT buses. Although the OPS cannot detect the smaller particles in the accumulation mode, a sharp increase in mass concentration of sub-micron particles is still visible in the OPS data (Fig. 4d).

The statistical summary of the concentrations recorded during the sampling campaign is compiled in Fig. 5 and Table 1. In-bus concentrations of $PM_{2.5}$, eBC, and CO were the highest compared to the other environments considered. The observed concentrations of eBC in this work are substantially higher than those reported in the literature, including studies reporting significantly high concentrations (Jeong et al., 2017). Similarly, only few studies known to the authors (e.g., Both et al., 2013; Chan et al., 2002) have reported higher CO levels inside public transport buses than those reported here. Mean in-bus concentration for the campaign was 176 $\mu g\,m^{-3}$ for $PM_{2.5}$, 92 $\mu g\,m^{-3}$ for eBC, and 6 ppm for CO (Fig. 5). Extreme cases were found in which average in-cabin concentration over a 17-min trip was 1203 $\mu g\,m^{-3}$ for $PM_{2.5}$, 717 for eBC, and 18.1 ppm for CO. In 45 different BRT buses mean $PM_{2.5}$ concentrations were higher than 200 $\mu g\,m^{-3}$. Similarly, in 52 out of 180 buses sampled the mean eBC in-cabin concentration was higher than 100 $\mu g\,m^{-3}$.

Urban ambient rush hour $PM_{2.5}$ concentrations for each sampling day are on average 8.2 times lower than corresponding observed in-bus concentrations. This high in-bus to ambient ratio suggests a strong deterioration of air quality levels inside the BRT buses. Although this ratio is calculated with respect to the fixed monitoring sites, it is consistent with the ratio of 6 that was reported by Morales Betancourt et al. (2017), when simultaneous side-by-side measurements of ambient and in-cabin $PM_{2.5}$ measurements were done. For the case of CO, the urban ambient rush hour concentration is 4.1 times lower than what was observed in-cabin of the BRT buses.

High in-station concentrations were also observed throughout the campaign, with mean in-station concentrations of the three pollutants ranking second among the micro-environments considered, only below the in-bus concentrations. Ratios of in-station to ambient concentrations were 5:1 for $PM_{2.5}$, and 2.6:1 for CO. From our results it is apparent that the ventilation of the bus stations is a key factor controlling the concentrations. Although terminal stations are typically surrounded by BRT bus traffic, concentrations in the terminal stations do not rank amongst the highest (Supplementary Material). Concentrations observed in the many regular stations were higher than on terminal stations. Of special concern were the pollution levels measured in the only underground station of the system, the National Museum Station (NMS), which was sampled 9 times during our campaign, for a total of 120 min. The mean concentration observed at NMS was the highest across all stations sampled, with $PM_{2.5}$ ranging between 253 $\mu g\,m^{-3}$ to 529 $\mu g\,m^{-3}$. Mean eBC was 232 $\mu g\,m^{-3}$, with a maximum mean concentration of 341 $\mu g\,m^{-3}$. Mean CO concentration at the underground station was 7.6 ppm.

Measurements during the campaign also revealed that exposure experienced during the walks towards or from the stations were significantly lower than either inside the BRT system stations or in the BRT system buses. Exposure to $PM_{2.5}$, eBC, and CO was higher in-bus, followed by in-station, with the lower concentration experienced by pedestrians. However, as can be seen from Table 1, the observed concentrations experienced by pedestrians in our study are comparable to those reported in the literature inside the cabins of buses.

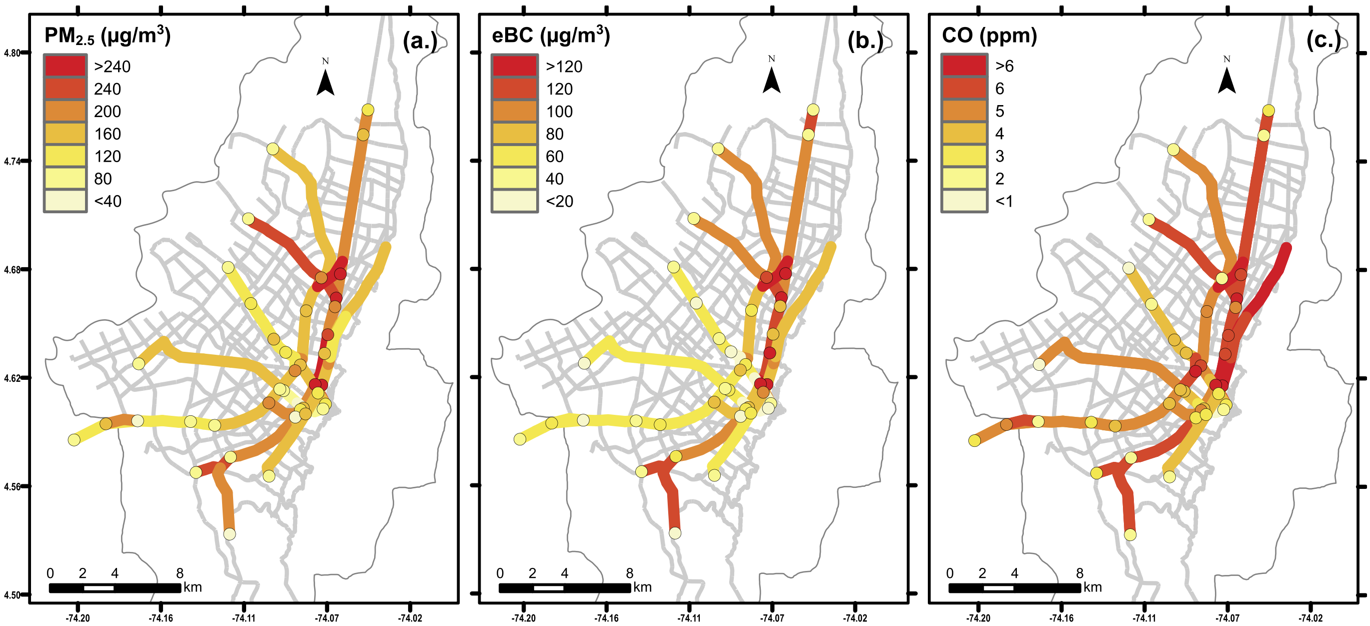

Fig. 3. Spatial distribution of observed concentrations in the BRT system throughout the sampling campaign for (a.) $PM_{2.5}$, (b.) *e*BC, and (c.) CO. Lines and circles represents segments and stations respectively. Color scale show median in-bus and in-station concentrations. The gray lines are the main road network of Bogotá. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Trip contribution to $PM_{2.5}$ and eBC daily dose

The potential inhaled dose of a given air pollutant, *j*, by users of the BRT system during a round trip, D^j_{trip} (μgday^{-1}), is calculated as

$$D^j_{trip} = \sum_{i \in trip}^{n_{trip}} C_i^j \, \mathrm{IR}_i \, \Delta t_i \tag{1}$$

where the summation is over the n_{trip} micro-environments associated with a trip in the BRT system, namely the walks towards the stations, the BRT bus-stations, and the BRT buses. In Equation (1) C_i^j (μg m^{-3}) is the concentration of pollutant *j* in micro-environment *i*, IR_i (m^{3}min^{-1}) is the inhalation rate associated with the activity level in the environment, Δt_i (min day^{-1}) is the time of exposure on each micro-environment. Although indoor air pollutant concentrations can be different from those in ambient air, the ratio of indoor to outdoor concentration depends on a large number of factors. However in studies of commuter's exposure it is commonly assumed that when individuals are in non-

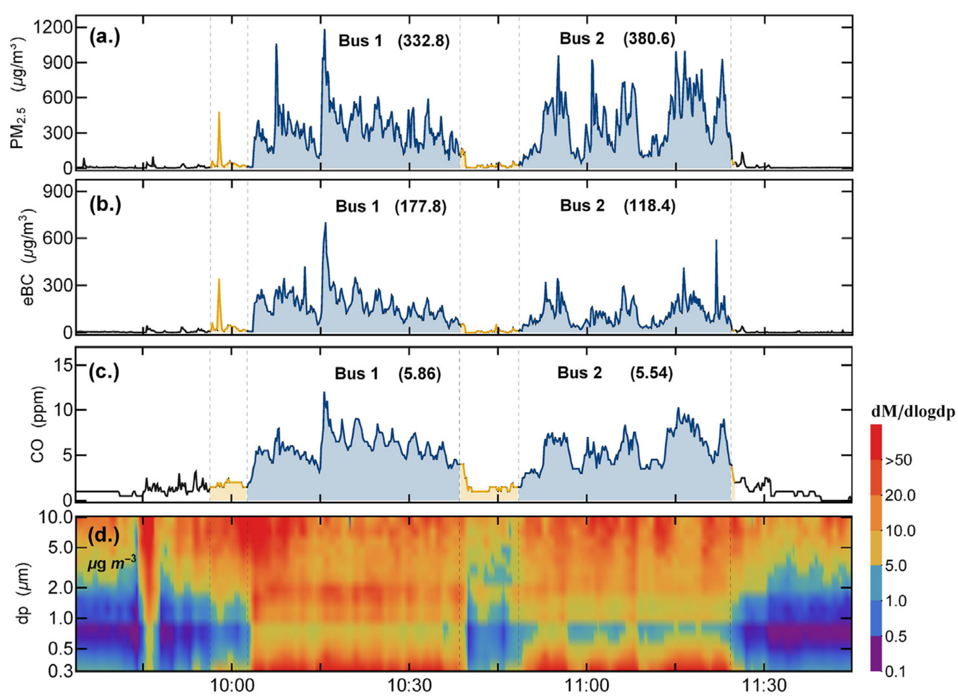

Fig. 4. Times series of (a.) $PM_{2.5}$ (μg m^{-3}) (b.) *e*BC (μg m^{-3}), (c.) CO, and (d.) Particle mass size distribution $dM/d \log d_p$ (μg m^{-3}) measured with the OPS. The blue shaded sections mark in-bus sampling, and yellow shaded region show in-station sampling. The number in parenthesis is the mean in-bus concentration. Sampling frequency is 15 s. Data was collected on a round trip on the BRT system during 2017/07/19. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

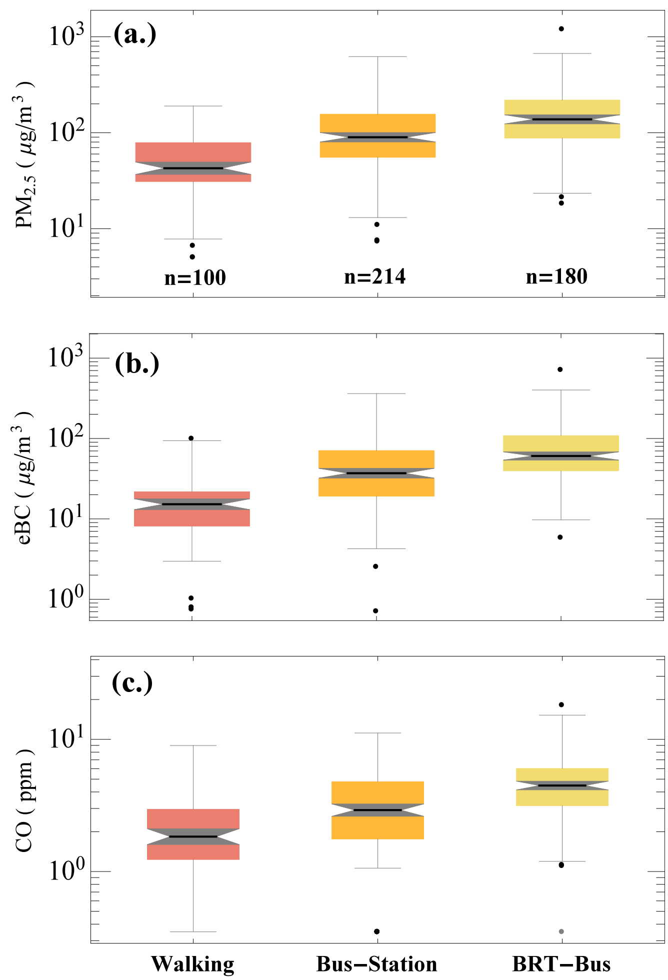

Fig. 5. Distribution of observed concentrations of (a.) $PM_{2.5}$, (b.) *e*BC, and (c.) CO. The data is partitioned according to the micro-environment sampled. *Walking* indicates the walking trips towards/from BRT stations, *Bus-Station* corresponds to the samples taken in the BRT bus stations, and *BRT-Bus* are measurements taken in-bus. The data shown here are average concentrations of each pollutant measured on each instance a specific micro-environment was sampled. The median of each distribution is marked with a dark black line. The notch in the box-plots is the confidence interval for the median estimate. Whiskers are the maximum and minimum values that are not outliers.

commute activities they are exposed to urban ambient concentrations (e.g., de Nazelle et al., 2012; Tainio et al., 2016), which are supposed to be representative of the long-term exposure of the individual. Furthermore, fixed monitoring air quality data has been the primary source for establishing associations between air pollution exposure and mortality (e.g., Dockery et al., 1993). In this study, the dose for the rest of the day, D^j_{rest}, is therefore estimated by assuming the individual is exposed to the urban ambient concentration reported by the air quality monitoring sites, C^j_{bg}.

$$D^j_{rest} = \sum_{i \notin trip}^{n_d - n_{trip}} C^j_{bg} \, \mathrm{IR}_i \, \Delta t_i \tag{2}$$

where n_d is the number of micro-environments the person occupies during a typical day. The individual is assumed to be sleeping for 8 h during the night ($\mathrm{IR}_{sleep} = 4.7$ LPM), performing light physical activity for 3 h ($\mathrm{IR}_{light} = 13$ LPM), and the remaining 13 h of the day excluding the BRT system travel time, involved in activities with a passive level of physical activity ($\mathrm{IR}_{passive} = 5.11$ LPM). The inhalation rates are those for a young adult, 20–30 years old, (US-EPA, 2011). The IR values used for each trip micro-environment are consistent with the average METs inferred from accelerometer data for each environment (Supplementary Material). The total daily dose is then computed as $D_{tot} = D_{trip} + D_{rest}$. To have a meaningful unit to quantify the potential dose inhaled in each round trip performed in the system, we compute the dose an individual exposed to the daily $PM_{2.5}$ WHO guidelines, $C_{\mathrm{WHO}} = 25 \mu g \, m^{-3}$, would inhale. Therefore, D_{WHO} is

$$D_{\mathrm{WHO}} = \sum_{i=1}^{n_d} C_{\mathrm{WHO}} \mathrm{IR}_i \Delta t_i \tag{3}$$

For the ventilation rate and activity pattern assumed in this study, $D_{\mathrm{WHO}} = 226 \, \mu g \mathrm{day}^{-1}$, a value similar to that reported by de Nazelle et al. (2012). By computing the inhaled dose for the full period of 24 h and the trip contribution we circumvent the normalization problem often discussed in exposure studies (Bigazzi and Figliozzi, 2014).

The average round-trip duration for our samples was 132 ± 32 minutes, which was only slightly shorter than the reported 140 min average duration of a round trip in the system. The total daily dose D_{tot} for both $PM_{2.5}$ and *e*BC as well as the trip contribution for all the measurement days can be seen on Fig. 6. On average, the estimated $PM_{2.5}$ daily dose was $D^{\mathrm{PM}2.5}_{tot} = 460.8 \mu g \mathrm{day}^{-1}$. This value is equivalent to two times D_{WHO}. Moreover, on average, a BRT round-trip alone accounts for 60.2% of the total $PM_{2.5}$ daily dose, with $D^{\mathrm{PM}2.5}_{trip} = 277.8 \, \mu g \mathrm{day}^{-1}$. This average daily dose associated with the trip alone, is equivalent to 1.2 times D_{WHO}. Furthermore, under the assumption that *e*BC is 17% of ambient $PM_{2.5}$ (See Section 2.2), the total daily dose of eBC was found to be $D^{e\mathrm{BC}}_{tot} = 174.1 \mu g \mathrm{day}^{-1}$. In this case, an alarming 79% of the daily *e*BC dose can be attributed to the BRT trip alone. If we assume our lower limit estimate for *e*BC/$PM_{2.5}$ of 8.7%, then even a larger fraction, 90%, of the daily *e*BC dose can be attributed to the BRT trip alone.

3.3. Exposure concentration and vehicle emission standard

The association between in-bus concentrations and vehicle nominal emission standard is explored by crossing the measured air pollutants concentration inside each individual BRT bus with the vehicle-specific characteristics. When the data collected during the campaign on-board 180 randomly sampled buses is partitioned based on the nominal emission standard of each individual bus, twice as large concentrations are observed in Euro II-III buses compared to concentrations measured in the newer Euro IV-V buses (See Fig. 7). For $PM_{2.5}$ mean (median) concentration in Euro II-III buses was 257 (218) $\mu g \, m^{-3}$ compared to 136 (112) $\mu g \, m^{-3}$ in Euro IV-V, a ratio of 1.9 for the mean concentration. For *e*BC mean (median) concentrations in the Euro II-III vehicles is 140 (108) $\mu g \, m^{-3}$ while it reduces to 63 (51) $\mu g \, m^{-3}$ for Euro IV-V. For CO, the reduction is from 5.9 (5.2) to 4.2 (3.7) ppm. The differences in the medians are statistically significant (Mann-Whitney test p-value ≤ 0.00001). It is highly unlikely that ventilation settings could explain these differences, since the vehicles were not sampled based on this parameter.

It should be noted that the nominal emission standard in the fleet is strongly correlated with VKTs and vehicle age. The 67 Euro II-III buses sampled have a mean 1.08×10^6 VKT and service time of 13.4 years, compared to 3.52×10^5 VKTs and 4.4 years for the 111 BRT buses sampled with nominal emission standard Euro IV-V. It is expected that emissions are higher for the Euro II-III vehicles, and that those emissions could be exacerbated by the considerable service time of those buses. Therefore, when the in-cabin concentration data is partitioned according to any variables describing vehicle age or emission standard, significant differences are observed. Further details can be found in the Supplementary Material.

Many factors could contribute to the substantial differences in in-cabin concentrations. As has been shown in other studies, self-pollution is a potential contributor to in-cabin concentrations (Marshall and Behrentz, 2005). Entrainment of emissions from nearby vehicles of all

Table 1
Statistical summary of concentrations reported in this study. *Walking* refers to the short walks towards/from BRT stations, the *In-Station* and *In-Bus* entries are samples taken in those BRT environments respectively. *Urban Ambient* data comes from the fixed monitoring sites in Bogotá as described in the text. *Other Studies* includes only in-bus data reported in two review papers (Kaur et al., 2007; Karanasiou et al., 2014) and other individual studies (Fernandez-Bremauntz and Ashmore, 1995; Both et al., 2013; Liu et al., 2015; Rivas et al., 2017; Goel et al., 2015; Tan et al., 2017; Li et al., 2015; Yang et al., 2015; Suarez et al., 2014), totaling 31 studies. The sample size, *n*, for each micro-environment is the number of instances were measurements were taken for periods longer than 3 min. The sample size for ambient concentration is the number of sampling days, and for *Other studies* is the average of the sample size reported in the studies. The highest value observed in each column is underlined. SD is the standard deviation, GSD is the geometric standard deviation.

Pollutant	Environment	n	Mean	SD	Median	GSD	Min	Max
$PM_{2.5}$ ($\mu g\ m^{-3}$)	Walking	98	55.6	38.1	42.7	2.15	5.0	189.8
	In-Station	208	130.0	113.8	89.7	2.39	7.4	621.7
	In-Bus	174	176.3	137.8	137.9	1.97	18.4	1203.1
	Urban Ambient	26	30.3	12.2	32.4	–	6.1	51.2
	Other studies (in-bus)	35	67.4	57.5	40.0	–	8.5	233.0[a]
*e*BC ($\mu g\ m^{-3}$)	Walking	100	18.9	17.3	15.2	2.35	0.8	99.9
	In-Station	214	63.8	72.4	37.0	2.85	0.7	361.8
	In-Bus	180	89.9	85.8	60.6	2.21	5.9	716.9
	Urban Ambient	–	–	–	–	–	–	–
	Other studies (in-bus)	30	15.8	14.3	8.8	–	3.2	50.0[b]
CO (ppm)	Walking	100	2.2	1.4	1.8	2.05	0.3	9.0
	In-Station	214	3.4	2.3	2.9	2.18	0.3	11.2
	In-Bus	180	4.8	2.5	4.5	1.82	0.3	18.2
	Urban Ambient	26	1.39	0.45	1.45	–	0.81	2.65
	Other studies (in-bus)	38	5.1	–	1.80	–	0.60	22.0[c]

[a] Delhi, India (Goel et al., 2015); [b] Ljubljana, Slovenia (Bizjak and Tursic, 1998); [c] Jakarta, Indonesia (Both et al., 2013).

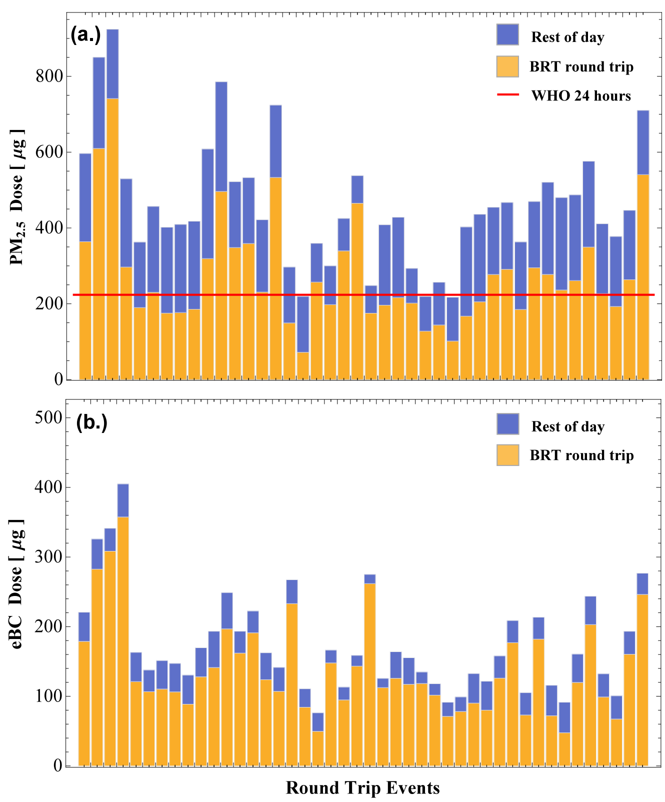

Fig. 6. Daily dose estimates for (a.) $PM_{2.5}$ and (b.) *e*BC. The stacked bars show the estimated dose during the trip only, D_{trip}, and the dose during the rest of the day, D_{rest}. Horizontal red line in (a.) indicates the value $D_{\mathrm{WHO}} = 226\ \mu g day^{-1}$. In the calculation of D_{rest}^{BC} it was assumed that 17.5% of $PM_{2.5}$ mass was Elemental Carbon (Ramírez et al., 2018), and assumed equivalent to *e*BC. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

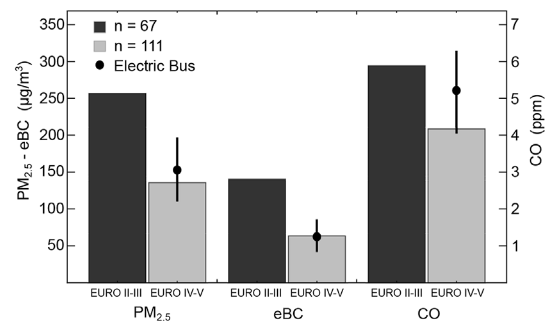

Fig. 7. In-bus $PM_{2.5}$ and *e*BC exposure concentration partitioned as a function of bus emission standard, for the 165 individual buses sampled.

types is likely a strong contributor to high in-bus concentrations. Stops for picking up passengers have also been identified as key determinants of in-cabin concentration excursions (Lim et al., 2015). Because of the configuration of the BRT system under study, surrounding traffic is mainly that of other BRT buses. This is particularly true at bus-stations. While a BRT bus is picking up passengers at a bus station, nearby buses can be either accelerating after having picked up passengers, or slowing down to stop at the same bus-station, or simply overtaking the stopped vehicle at cruise speed. All this activities will likely contribute to the admission of polluted air to the cabin and to the station. Furthermore, bus operators which own the older vehicles are in charge the operation of specific branches of the system. Therefore, there are branches with mainly older buses circulating in them. However, this separation becomes increasingly difficult as are portion of the BRT lanes that are used by all the buses irrespective of the specific operator. The map on Fig. 3 show that some specific corridors have higher concentrations. This explains in part the very large differences observed between in-cabin exposure in older and newer buses.

Further evidence suggest that a substantial portion of the in-cabin and in-station air pollution is likely the result of fumes entrained from other BRT buses, and potentially, from self-contamination as well. First, our measurements show there is a large contribution of *e*BC to the $PM_{2.5}$ across the system. Particulates rich in Elemental Carbon are more likely to come from diesel combustion (Zielinska et al., 2004; Maricq, 2014). The particulates coming from mixed traffic, which are mostly gasoline vehicles that use the adjacent lanes, or the industrial sources which are sparse and far away from the BRT system, or even the urban background, all should have a lower *e*BC content.

Data supporting such hypothesis are the measurements performed simultaneously inside and outside the National Museum underground

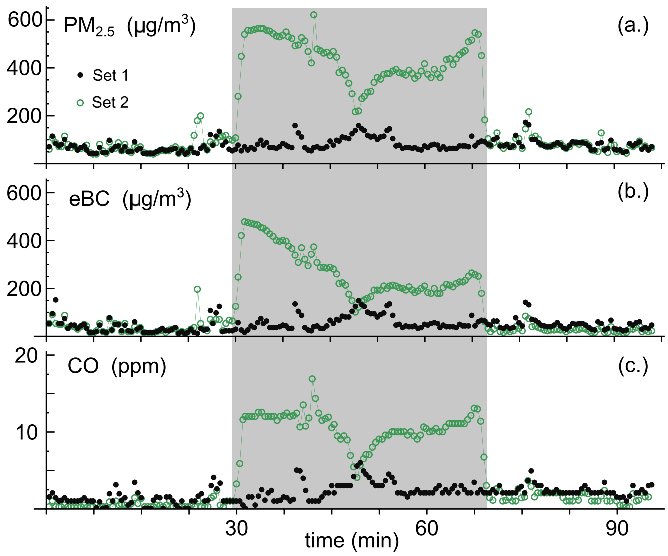

Fig. 8. Measured concentrations of (a.) $PM_{2.5}$, (b.) *eBC*, and (c.) CO. Measurements were performed inside a BRT underground station (open circles, shaded region) and outside the station (black filled circles, and open circles in the not-shaded region).

station using two sets of sampling devices. In the first 30 min of sampling both sets were side-by-side at the sidewalk above ground, next to the mixed-traffic lanes that pass on top the underground station. Then, one of the teams entered the underground station for 40 min, then emerged and sampled again side-by-side (Fig. 8). These measurements show that concentrations inside are 5.7, 6.2 and 2.6 higher for $PM_{2.5}$, *e*BC, and CO respectively. These ratios are comparable to the observed in-cabin to ambient, or in-station to ambient reported in Section 3.1. *e*BC to $PM_{2.5}$ ratio inside the underground station increases to 0.6 from 0.3 at the sidewalk. These *e*BC to $PM_{2.5}$ ratios inside this station are very similar to those found inside buses or stations above ground. However given the forced ventilation system at the underground station blows inside air out, and the large mismatch between inside and outside concentrations (Fig. 8), it is very unlikely that sources different to the BRT buses are causing the alarmingly high concentrations. In this tunnel, exhaust fumes from the diesel-powered vehicles are the only combustion sources.

Additional evidence for this hypothesis comes from measurements performed on-board an electric BRT bus over a 4-h period. The observed concentrations were not significantly different from those inside the Euro IV-V portion of the fleet (Fig. 7). We identified higher pollutant concentrations at the parking lot, as well as at the bus stations. Given that the parking lot is far from other traffic lanes, its likely pollutants come from the system buses. At the stations, peaks in concentrations occurred when the bus doors opened, or other buses accelerated to overtake the stopped electric bus.

The potential reduction in daily dose of commuters using the BRT, D_{tot}, that could be achieved with a renewal of the bus fleet, can be estimated with the data-set reported in this study. For that purpose, we assumed all Euro II-III vehicles would be replaced by Euro IV-V nominal emission standard vehicles, and therefore, the average exposure level in those older vehicles would be replaced by the average exposure measured inside the Euro IV-V. Our measurements show a ratio of $PM_{2.5}$ in newer buses to average in-bus $PM_{2.5}$, $f_{PM_{2.5}} = PM_{2.5}^{new}/PM_{2.5}^{avg}$ equal to 0.77. Assuming travel times, travel time distribution in micro-environments, and urban background concentrations remain the same in the system, and by further assuming the new in-bus average concentration should be equal to that of the current Euro IV-V vehicles, the expected reduction in total daily dose, R, can be shown to be

$$R = 1 - \frac{D_{tot}^{new}}{D_{tot}^{old}} = (1 - f_{PM_{2.5}})F_{BRT} \approx 0.1 \quad (4)$$

were, F_{BRT} is the current fraction of the daily dose attributable to the trip in the BRT. Therefore, a reduction of approximately 10% of the daily dose of $PM_{2.5}$ for commuters using the BRT system could be expected just from assuming all old buses are replaced with newer vehicles. This is a conservative estimate since it assumes that the exposure reduction is only felt during week days and neglects any potential reduction in exposure associated with the removal of the high-emitting vehicles. When the calculation is repeated for *e*BC a reduction of 16%–18% could be expected. This substantial reduction in daily exposure to air pollutants for commuters is only possible due to the extremely large in-bus to ambient concentration gradients documented in this work. For a mass transit system like the BRT of this study, this potential reduction could positively impact the 1.2 million people that use the system on a daily basis. The findings of this study suggest that a renewal of the fleet, or its replacement with low-emitting vehicles, could have a disproportionately large effect in the reduction of air pollution exposure and daily dose for commuters.

4. Conclusions

The concentration of $PM_{2.5}$, *e*BC, CO, and the size distribution of aerosol particles was measured in micro-environments associated to a Bus Rapid Transit System in the city of Bogotá, Colombia. Extremely high concentrations of all the monitored pollutants were observed inside the bus cabins as well as in the interior of the system stations. The in-bus average concentration was 176 $\mu g\, m^{-3}$ of $PM_{2.5}$, 90 $\mu g\, m^{-3}$ of *e*BC, and 4.8 ppm of CO. Extreme cases were observed in which average in-bus concentrations of $PM_{2.5}$ reached levels as high as 1200 $\mu g\, m^{-3}$, and over 700 $\mu g\, m^{-3}$ of eBC. The observed in-bus concentrations were the highest among the micro-environments considered in this study. Furthermore, the observed concentrations are much higher than those reported in the available literature.

A sharp increase in air pollution levels was observed in the micro-environments associated with the BRT system. In-bus *e*BC concentration was 50% of $PM_{2.5}$ mass, suggesting a strong contribution from diesel combustion emissions to the $PM_{2.5}$ exposure concentration. Similarly, high exposure concentrations were found in the interior of bus stations. Concentrations higher than 500 $\mu g\, m^{-3}$ of $PM_{2.5}$ with a *e*BC contribution of up to 60% were observed in an underground station in which traffic is restricted only to BRT vehicles. The high soot content of fine particle mass inside the BRT vehicles and stations suggests that a substantial fraction of the air pollutants inside the BRT system buses comes from either the same bus or the surrounding BRT buses.

Estimates of the contribution of a round-way trip in the BRT system were performed, finding that on average it can account for 60% of $PM_{2.5}$ daily dose. The average round-way trip dose is equivalent to 1.2 times the average daily dose a person would receive during a 24 h exposure to the WHO guidelines for $PM_{2.5}$. The contribution of a typical BRT trip to daily *e*BC dose was estimated to be between 79% and 89%.

The data in this study shows that regardless of the month-to-month variations in air pollution levels in the city, in-bus and in-station concentrations are several times higher than ambient concentrations even in the months with higher-than-average air pollution levels.

The in-bus concentration data was partitioned based on the nominal emission standard attained by the individual buses monitored. The in-bus exposure concentration was significantly higher for vehicles with nominal Euro II-III standards compared to those with Euro IV-V nominal standards. Almost a two-fold increase was observed for both $PM_{2.5}$ and *e*BC, while a 1.4 increase was detected for CO. Given the association between vehicle emission standard and in-bus concentration exposures, our findings suggest that a renewal of the fleet and a replacement with vehicles with stricter emission standards could have a disproportionately large effect in the reduction of air pollution exposure. The relevance of this potential reduction is considerable given the large population exposed daily to these pollution levels. Such reduction in exposure is only possible provided the large gradient in concentration between ambient and transport related environments.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2019.01.026.

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