Atmospheric Environment 157 (2017) 135–145

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Exposure to fine particulate, black carbon, and particle number concentration in transportation microenvironments

R. Morales Betancourt [a, *], B. Galvis [b], S. Balachandran [c], J.P. Ramos-Bonilla [a], O.L. Sarmiento [d], S.M. Gallo-Murcia [a], Y. Contreras [a]

[a] Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia
[b] Program of Environmental and Sanitary Engineering, Universidad de la Salle, Bogotá, Colombia
[c] Department of Biomedical, Chemical and Environmental Engineering, University of Cincinnati, Cincinnati, OH, United States
[d] School of Medicine, Universidad de Los Andes, Bogotá, Colombia

HIGHLIGHTS

- Dose of commuters to $PM_{2.5}$, black carbon, and ultrafine particles was measured.
- Exposures were 6 times higher in public buses than for pedestrians, and 10 times background level.
- Street geometry had great impact on exposure with twice as large PM pollution in street canyons.
- Presence of dedicated bike lanes was shown to reduce exposure of cyclists to PM pollution.
- Car passengers were exposed to the lowest inhaled dose.

ARTICLE INFO

Article history:
Received 11 October 2016
Received in revised form
2 March 2017
Accepted 6 March 2017
Available online 14 March 2017

Keywords:
Fine particulate
Black carbon
Pollution in urban microenvironments in latin-America
Ultrafine particles
Micro-aethalometer loading correction

ABSTRACT

This research determined intake dose of fine particulate matter ($PM_{2.5}$), equivalent black carbon (*e*BC), and number of sub-micron particles (N_p) for commuters in Bogotá, Colombia. Doses were estimated through measurements of exposure concentration, a surrogate of physical activity, as well as travel times and speeds. Impacts of travel mode, traffic load, and street configuration on dose and exposure were explored. Three road segments were selected because of their different traffic loads and composition, and dissimilar street configuration. The transport modes considered include active modes (walking and cycling) and motorized modes (bus, car, taxi, and motorcycle). Measurements were performed simultaneously in the available modes at each road segment. High average *e*BC concentrations were observed throughout the campaign, ranging from 20 to 120 $\mu g\ m^{-3}$. Commuters in motorized modes experienced significantly higher exposure concentrations than pedestrians and bicyclists. The highest average concentrations of $PM_{2.5}$, *e*BC, and N_p were measured inside the city's Bus Rapid Transit (BRT) system vehicles. Pedestrians and bicycle users in an open street configuration were exposed to the lowest average concentrations of $PM_{2.5}$ and *e*BC, six times lower than those experienced by commuters using the BRT in the same street segment. Pedestrians experienced the highest particulate matter intake dose in the road segments studied, despite being exposed to lower concentrations than commuters in motorized modes. Average potential dose of $PM_{2.5}$ and *e*BC per unit length traveled were nearly three times higher for pedestrians in a street canyon configuration compared to commuters in public transport. Slower travel speed and elevated inhalation rates dominate PM dose for pedestrians. The presence of dedicated bike lanes on sidewalks has a significant impact on reducing the exposure concentration for bicyclists compared to those riding in mixed traffic lanes. This study proposes a simple method to perform loading effect correction for measurements of black carbon using multiple portable aethalometers.

1. Introduction

The negative health impact of exposure to particulate matter and other air pollutants is well known (e.g., Pope et al., 1991; Nyhan

---

* Corresponding author.
E-mail address: r.moralesb@uniandes.edu.co (R. Morales Betancourt).

http://dx.doi.org/10.1016/j.atmosenv.2017.03.006
1352-2310/

et al., 2014; Kingham et al., 2013). Commuters can be repeatedly exposed to peak concentrations of air pollutants (e.g., Gulliver and Briggs, 2004; Kaur et al., 2007; Li et al., 2015), up to three times higher concentrations than background (Krzyżanowski et al., 2005). Therefore, for many city dwellers, a significant fraction of their daily exposure to air pollutants may occur in transportation microenvironments. Commuting can account for 21% of personal exposure to black carbon and approximately 30% of inhaled dose (Dons et al., 2012). Commuting times average 260 h per year worldwide and can be twice that amount in cities with mobility challenges (Moraes and Schwanen, 2015). Exposure during highway commutes is associated with measurable impacts on health (Sarnat et al., 2014), and peak exposures in short periods of time are thought to have substantial health impacts (Michaels and Kleinman, 2000).

Due to its significant contribution to pollutant exposure, transportation microenvironments have been the subject of many studies. For the most part, studies indicate that travelers inside different types of vehicles are exposed to higher levels of particulates and other pollutants than pedestrians or cyclists (e.g., Berghmans et al., 2009; Boogaard et al., 2009; Int 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). Nonetheless, there are some studies showing higher exposures to $PM_{2.5}$ for pedestrians (e.g., Liu et al., 2015). A large degree of variability in the exposure of commuters to air pollutants is recognized (Yang et al., 2015). Several factors might influence this variability. These factors can be sorted into two groups; those related to the travel modes (i.e., the transport system, technology, or energy source) and others related to characteristics of the path traveled (i.e., street configuration, micrometeorology, or traffic loads) (Hertel et al., 2008). Recent studies have investigated the factors controlling the variability in personal exposures for many contaminants, finding that the transportation modes explain a significant portion of it (de Nazelle et al., 2012). However, these studies recognize that an important part of the variability for $PM_{2.5}$ remains unexplained. The influence of traffic in exposure variability has been investigated in other studies finding a lower exposure during weekend trips and higher during commute trips in weekdays, mainly because they occur at rush hour (e.g., Dons et al., 2012). Xie et al. (2006) found that street configuration might also play an important role in the variability of exposure measurements. These last two studies found that commuters that take less congested and well-ventilated streets are exposed to lower concentrations of pollutants.

More recently, the focus has been placed on quantifying not only the mass of particulate matter to which commuters are exposed to, but the number concentration of particles. Freshly emitted soot might be an important component of the particulate exposure for commuters, both in number and mass, because of the proximity of commuters to the sources (e.g., Liu et al., 2015; Fernandez-Bremauntz and Ashmore, 1995). Moreover, automotive exhaust emissions are known to contain large number concentration of ultra fine particles (UFP). These particles are not always well represented in traditional mass-based particulate measurements, but might have pronounced effects on health (Ragettli et al., 2013).

A comprehensive review of exposure studies in European cities is provided in Karanasiou et al. (2014). However, similar studies are not often performed in cities of emerging economies, which might have serious air pollution problems. In Latin America Suarez et al. (2014) analyzed personal exposure to $PM_{2.5}$ and UFP in commuters using different transport modes in Santiago, Chile. They compared personal exposure to monitoring site measurements. They found that monitoring sites often underestimate personal exposure. Fajardo and Rojas (2012) estimated exposure of cyclists on a dedicated bike-lane in Bogotá using gravimetric methods to measure PM_{10} at fixed locations along the path. The study found 8-h-average PM_{10} exposure concentrations between 78 and 108 $\mu g\ m^{-3}$. Franco et al. (2016) measured $PM_{2.5}$ and *e*BC concentrations for cyclists in Bogota's bike paths and found approximately 2.3 and 1.4 times greater concentrations on weekdays than on weekends for each of those contaminants respectively. They also reported that $PM_{2.5}$ concentrations far exceeded standards.

From the perspective of inhaled dose, the increased respiratory rate of commuters in active modes of transport (e.g., pedestrians and cyclists) might imply an elevated dose of traffic-related pollutants (Zuurbier et al., 2010). It has been found that intake doses for bicyclists are often higher than dose for users of other modes (e.g., Bigazzi and Figliozzi, 2014). The majority of studies assessing commuter exposure to air pollutants have been carried on in European cities with large number of bicycle users.

This study assesses some of the aspects influencing particulate matter exposure and inhaled dose in transport microenvironments in a large and rapidly growing metropolitan area. The study is designed to identify the impact of transport alternative on inhaled dose by quantifying and comparing the dose of commuters performing the same trip. In order to compile a thorough data set, we performed numerous simultaneous measurements of personal exposure concentration of fine particulate mass, $PM_{2.5}$, sub-micron particle number concentration, N_p, and equivalent Black Carbon, *e*BC, concurrently in several transportation modes. Additionally, measurements of the physical activity level of the commuters on each mode of transport were performed, and travel times and speeds were determined. The study covered almost all of travel mode alternatives in the city, and explored the effects of traffic volume, composition, and street configuration.

2. Methods

The measurement campaigns in this study were designed to isolate the impact of transport alternative on particulate matter dose. For this purpose, exposure concentrations of $PM_{2.5}$, *e*BC, and N_p were measured for commuters performing the same trip, traveling a predefined path simultaneously using different transportation alternatives. Detailed description of the measurement campaigns are described here.

2.1. Transportation modes studied

We considered two active modes of transport, walking and cycling. Public transport buses, taxis, cars, and motorcycles were included in the study. Measurements were also performed in the city's BRT system, one of the largest in the world, currently carrying 2.4 million travelers everyday. Together the transportation modes considered in this study encompass almost all of the travel alternatives in the city.

2.2. Study area

Three corridors were selected for this study. The locations within the city limits are shown in Fig. 1. The road segments selected have similar length but widely different traffic composition and load. The geometries of the street segments range from a wide avenue to a street canyon configuration (Fig. 2). Segment 1 (80th Street) has five lanes in each direction of traffic, two of them used by the BRT and three lanes of mixed traffic. The buses that serve this BRT line are articulated and bi-articulated diesel buses, with lengths of 18 m and 25 m respectively, and carrying capacity of up to 140 and 250 passengers respectively. The segment has a

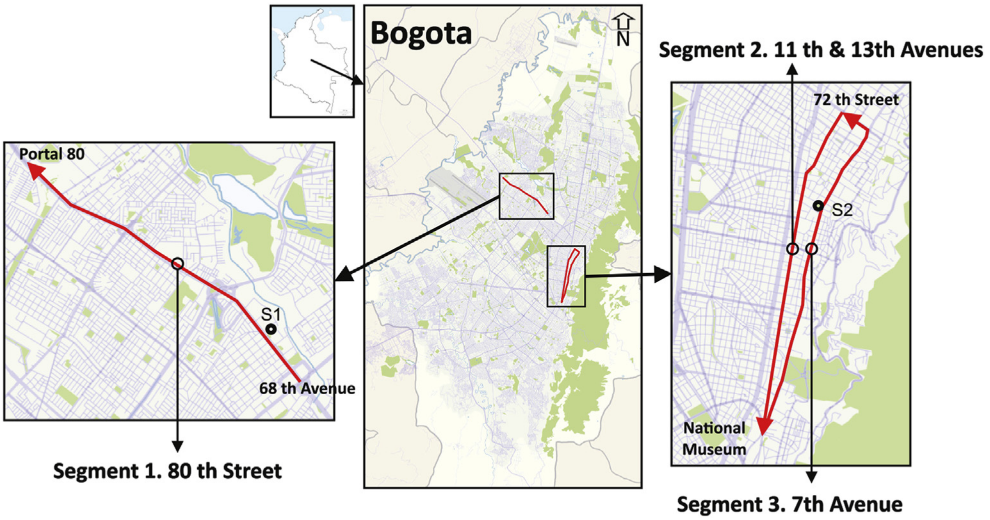

Fig. 1. Location of the three road segments selected for this study. The three corridors are located in the central part of the city. The lengths of the segments are all within 4.5–4.9 km S1 and S2 denote the location of neighboring air quality monitoring sites.

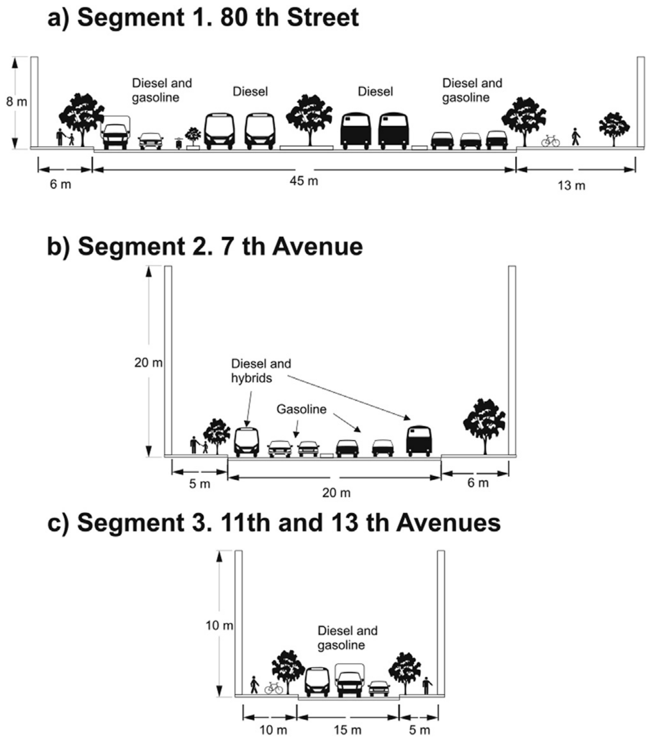

Fig. 2. Cross-section geometry and vehicle technology for each street segment considered in this study. (a.) Segment 1–80th Street. (b.) Segment 2–7th Ave. (c.) Segment 3–11th and 13th St.

dedicated bike-lane, built on the sidewalk (Fig. 2). Segment 2 (7th-Avenue), is a six lane avenue, three in each direction, which hosts a variety of transportation modes. It has one dedicated lane for public transport buses in each direction. This line is used by hybrid (Diesel/ electric) buses with a capacity of up to 80 passengers. This lane also hosts smaller diesel buses of different sizes. This street does not have dedicated bike-lanes. Lastly, Segment 3 (11th & 13th Avenue) is a smaller 3-lane street with only one direction of traffic. Its lanes are shared by cars, motorcycles and a large number of small public transport diesel buses. As in Segment 1, this street has a dedicated bike-lane built on the sidewalk. The characteristics of the three corridors are detailed in Table 1. For further details on traffic loads and composition see Supplementary Material.

2.3. *Measurements of particulate matter*

2.3.1. *$PM_{2.5}$ mass concentration*

The mass concentration of $PM_{2.5}$ was measured at 1 Hz with a laser scattering based method (DustTrack 8520 and DustTrack DRX, TSI Inc. MN, USA). These instruments (DT hereafter) use laser wavelengths of 780 and 640 *nm* respectively. The size selection of the sampled particles is performed through an inertial impactor placed at the instrument inlet (DT model 8520 only). Flow calibration was performed before each use to ensure proper particle aerodynamic size selection. A thorough inter-comparison of the five DT instruments used in this study was performed in a laboratory environment prior to the campaign. The instruments showed excellent agreement, with 30-s averaged data showing a correlation coefficient of 0.90. The bias across instruments was ±15%. The reported instrument accuracy is $\pm 1 \mu g\ m^{-3}$.

Laser-based PM instruments are known to have biases when measuring ambient aerosols, caused by the chemical composition and size distribution dependence of laser scattering intensity. To account for this, a comparison of the average $PM_{2.5}$ concentration reported by the DT was performed against a gravimetric method. A set of Personal Environmental Monitors (PEMs) (SKC Inc. PA, USA) were utilized for this purpose. The PEM is a personal sampling device for PM, consisting of a single-stage $PM_{2.5}$ impactor and

Table 1
Characteristics of the street segments selected for this study. The BRT system operates in Segments 1 (80th street) and Segments 2 (7th-Avenue). Segment 1 has two exclusive BRT lanes in each direction, for articulated and bi-articulated buses, while Segment 2 has one preferential BRT lane for mid-sized buses.

Segment ID	Segment 1	Segment 2	Segment 3
Street Name	80th Street	7th-Avenue	11th & 13th Ave.
Length	4.5 km	4.7 km	4.9 km
Number of Lanes	10	6	3
Principal BRT Lanes	Yes* (4)	No	No
Preferential Bus Lane	No	Yes** (2)	No
Dedicated Bike Lane	Yes	No	Yes
Street Configuration	Open	Intermediate	Street Canyon

37 mm PTFE collection filter, with a sampling flow rate of two LPM. The flow rate was calibrated before and after the sampling period with Defender 510 and 520 flow calibrators (DryCal - Mesa Labs, Butler, NJ, USA). Two PEMs were sent in each transportation mode together with at least a DT instrument. Due to the relatively short sampling periods (100–140 min), careful screening of the gravimetric data was performed to ensure that enough mass was collected on the filters. Only those measurements in which the mass concentration computed for the duplicate PEMs were within 15%, and the mass collected was $\geq 20\mu g$ were used. A linear response between the average DT concentration and the gravimetric PEM method was found, with a correlation coefficient of 0.92. The slope of the linear fit was 0.64 and an intercept of $50\mu g\ m^{-3}$ (See Supplementary Material).

In order to determine the effect of background air pollution in the day-to-day variations of measured exposure concentration, $PM_{2.5}$ data from central air quality monitoring sites was used. However, few of the air quality monitoring stations in the city monitor $PM_{2.5}$, and none of them are urban background stations. Neither *e*BC or N_p are measured in the city. The two stations chosen for this study, denoted S1 and S2 (Fig. 1), are considered as *traffic* monitoring sites. This is somehow problematic as a measure of background pollution levels, but are nonetheless useful to quantify the day-to-day changes in air pollution in the surrounding area. The average of hourly $PM_{2.5}$ data between 7am and 10am on the measurement days was used to characterize such background concentration.

2.3.2. Light-absorbing aerosol concentration

The *e*BC data was collected with a set of five hand-held micro-Aethalometers (MicroAeth AE51, AethLabs, CA, USA). The raw *e*BC was corrected to account for the low atmospheric pressure in Bogotá (755hPa). The nominal flow rate in the instrument was set to 150 $cm^3\ min^{-1}$. The data was also corrected for filter loading effects. This artifact is well known to affect *e*BC measurements made with instruments based on attenuation of light through a spot in a filter (e.g., Virkkula et al., 2007, 2015). However, this effect often not accounted for in studies with portable AE51. A linear correction method for the *e*BC was applied to the measurements (Virkkula et al., 2007; Cheng and Lin, 2013),

$$eBC = eBC_0(1 + k(ATN - ATN_0)) \quad \text{for} \quad ATN > ATN_0 \tag{1}$$

where eBC_0 is the uncorrected *e*BC, *ATN* is the attenuation in the filter spot, and $ATN_0 = 20$. Simultaneous, synchronized eBC_0 measurements taken in the same microenvironment by two or more AE51, each one with a different level of *ATN*, were utilized to infer the value of the loading correction constant *k*. It was assumed that those measurements for which $ATN < 20$ had a negligibly small loading effect so $eBC_0 \approx eBC$. The factor *k* was then statistically inferred as the one that would bring the *e*BC measured by another AE51 with larger value of *ATN* in agreement with the reference instrument. The mean value obtained following this procedure was $k = 0.01$. This correction factor is consistent with findings in other studies with the same portable instrument (Cheng and Lin, 2013). The reported accuracy of the instrument is ±100 $ng\ m^{-3}$. To minimize noise, the instruments were configured to report 30 s averages of *e*BC. Only data with a maximum attenuation of 140 was reported. In some instances, filters were allowed to exceed this maximum attenuation, but only when duplicate equipment with a fresh filter was present. In this cases, the data from the heavily loaded AE51 was used to infer the loading factor *k*, and the corrected data from the less loaded AE51 was used to report *e*BC concentration.

2.3.3. Particle number concentration

N_p was measured with a miniature diffusion size classifier (Fierz et al., 2011), commercially available as DiSCmini (Matter Aerosol, Wohlen, Switzerland). The instrument reports N_p, alveolar lung deposited surface area, and the mean particle diameter. The smallest detectable particle diameter in the DiSCmini is ~ 20 nm, allowing almost the complete detection of accumulation mode particles, and some fraction of the nucleation mode particles. In this study, the DiSCmini was always used with an impactor at the inlet to prevent particles larger than 600 nm from entering the instrument. The instrument has previously been shown to agree well when compared to condensation particle counters (Asbach et al., 2012; Meier et al., 2013). The instrument precision is reported to be ±30% for N_p.

2.4. Physical activity and inhalation rate

In-situ information of physical activity level associated to each commute alternative was collected using GT3X + portable activity monitors (Actigraph GT3X+, Ft. Walton, FL.). This device measures acceleration in three-axis, at a frequency of 30 Hz. Correlations have been developed to transform acceleration data to Metabolic Equivalence Units (METs) (e.g., Freedson et al., 1998). METs are associated with the level of physical activity and inhalation rate. Accelerometer data has been shown to be strongly correlated with ventilation rate (e.g., Kawahara et al., 2011). The GT3X + are typically placed in the hips of the subject. However, measurement of physical activity of bicyclists using accelerometers is challenging, since the placing of the instrument can greatly impact the results. When the activity monitor is placed on the hips of the cyclist, the activity counts are too low, implying an unrealistically low level of physical activity. For this reason, and for cyclists only, the ActiGraph was placed on the ankle of the subjects, as has been done in other studies (e.g., Zhang et al., 2012). The inhalation rate associated to each activity level was selected from the EPA's Exposure Factor Handbook - Table 6.17 (US-EPA, 2011), for young adults aged 21–31 years (see Table 2). For active modes of transport, the activity level is also affected by the speed of travel. Higher speeds are associated with higher energy expenditure and increased inhalation rate. To account for this, and ensure that the appropriate physical activity level was used, the GPS-derived velocity was measured and compared with reported literature values for the specific activity (Ainsworth et al., 2000). Due to equipment availability, physical activity data was not always collected simultaneously with air pollution measurements, but was collected on the same exact street segments by subjects performing the same activities as when air pollution data was being collected.

2.5. Data collection

In a typical sampling day, all the participants in the study were asked to meet at a designated starting point, and to travel the selected street segment from that point to another previously defined finish point. For a given street segment, the starting and finish points were the same throughout the campaign.

Table 2
Inhalation rate and energy expenditure for each activity level (US-EPA, 2011).

Activity Level	Energy Expenditure	Inhalation Rate
Classification	(METs)	$(m^3 min^{-1})$
Sedentary	METs$\leq$ 1.5	5.11×10^{-3}
Light	$1.5 <$ METs$\leq$ 3.0	1.30×10^{-2}
Moderate	$3.0 <$ METs$\leq$ 6.0	2.92×10^{-2}
Vigorous	METs> 6.0	5.39×10^{-2}

Measurements started from the moment the participants began their trip. Therefore, the exposure concentration data was collected simultaneously for all the transport alternatives in a given day. In this way, it is ensured that all travelers are performing the same trip, except for the choice of transportation mode. Furthermore, the effect of background concentration should be the same for all modes.

Measurements were performed during two stages. The first stage of the campaign, consisted of nine sampling days from July 23 to August 5 of 2015. In this first campaign, the three road segments described in Table 1 were surveyed with continuous monitoring devices. A total of five DT $PM_{2.5}$ monitors, five AE51 *e*BC monitors, and two DiSCmini particle counters were utilized during these measurements. Therefore, up to five modes of transportation could be monitored simultaneously. However, in order to check the reproducibility of the measurements and instrument proper functioning, duplicate equipment was often sent in the same transport mode. In addition to the continuous monitoring instruments, 10 PEMs, two on each transport mode surveyed, were employed in each day of the campaign to measure the integrated $PM_{2.5}$ concentration. Pedestrians took 60–70 min to complete one transect from starting point to the final meeting point. Commuters in other modes took typically a third of that time or less. In order to extend sampling times, participants in all modes were asked to travel the segment three times, except for pedestrians. However, during these sampling periods not enough PM mass was collected in the filters to be accurately determined gravimetrically. Therefore, for Stage 1 of the field campaign only the data collected with the continuous monitoring equipment is reported.

During the second stage of the campaign data was collected exclusively on Segment 1 during 19 sampling days between September and November of 2015. During the second stage, pedestrians were asked to travel the road segment two times, once in each direction, while all the other modes traveled the segment five times. The resulting sampling times were between 100 and 140 min allowing the collection of enough mass for accurate gravimetric determination of $PM_{2.5}$. Ten PEMs were employed in each day of the campaign, with duplicate equipment sent on each of five transport modes. Together with the PEM impactors, three DT $PM_{2.5}$ monitors and two AE51 *e*BC monitors were used. Overall during both measurement campaigns there were 29 sampling days, and a total of 190 filter based $PM_{2.5}$ samples were collected. The measurements took place exclusively on weekdays and during the morning rush hour, between 7am and 10am. A detailed record of commuter activities during each trip (e.g., entering or exiting a BRT station, reaching a bus stop, reaching a busy interception, etc.) was kept. Pedestrians and cyclists were equipped with GPS units for geolocation of the measurements and to determine travel times and speed. The clocks of all the instruments were synchronized to the GPS clock. The measurement campaign involved participation of nearly 15 people each day. The instruments used in the campaign are all portable and were carried in backpacks by the participants in the study, with the sample inlet located in the breathing zone. Detailed schedule of the field campaigns can be found in Supplementary Material.

2.6. Potential dose

The potential dose inhaled by commuters during a trip from starting point to end point, on transport mode *i*, and road segment *j*, is controlled by the exposure concentration, $C_{i,j}$ (μg m^{-3}), the inhalation rate associated with the typical activity for each transport mode, IR_i (m^{3}min^{-1}), and the duration of exposure $\Delta t_{i,j}$ (*min*). For our case, the duration of exposure equals the travel time from initial point to final point. The potential dose for a commuter during the time it takes to complete a trip, $D_{i,j}$ (μg), can be calculated as,

$$D_{i,j} = C_{i,j}\mathrm{IR}_i\Delta t_{i,j} \tag{2}$$

During the field campaign $C_{i,j}$ and $\Delta t_{i,j}$ were directly measured (Section 2.3). The level of physical activity inferred from the activity monitors was then used to establish the appropriate IR_i from reported literature values (Section 2.4).

For a given street segment Equation (2) represents the dose commuters experience per trip. A normalization factor is often applied to make dose measurements comparable across travel modes and to studies performed in segments of different lengths. Many normalization alternatives are used in the literature (Bigazzi and Figliozzi, 2014). Three such normalizations alternatives are explored here, dose per unit length, $D^L_{i,j}$ (μgkm^{-1}), dose per unit time, $D^t_{i,j}$ (μg min^{-1}), and total dose, $D^{Tot}_{i,j}$ (μg),

$$D^L_{i,j} = D_{i,j}/L_j \tag{3a}$$

$$D^t_{i,j} = D_{i,j}/\Delta t_{i,j} \tag{3b}$$

$$D^{Tot}_{i,j} = D_{i,j} + C_{bg}\mathrm{IR}_{bg}(t_{max} - \Delta t_{i,j}) \tag{3c}$$

where L_j is the length of the road segment, C_{bg} is the background concentration, IR_{bg} is the inhalation rate associated with the time not spent in the transport microenvironment, and t_{max} is the total time over which the dose is to be computed. Normalizing $D_{i,j}$ by L_j (Equation (3a)) allows comparisons of dose for trips of different lengths. This metric is dependent on the speed of the particular travel mode, i.e., if a transport mode is slower, then $\Delta t_{i,j}$ will be large, increasing the exposure for slower modes. This approach has the disadvantage that for faster trips, the time spent in the destination environment is typically neglected (Bigazzi and Figliozzi, 2014). This problem can be circumvented in two ways, either normalizing by travel time (Equation (3b)) or computing the total dose for a fixed period of time t_{max} (Equation (3c)). The normalization by unit time circumvents the problem of comparing dose for different exposure times, but does not take into account the speed of travel. D^{Tot} is computed in this study, by assuming $t_{max} = 80$ min, equal to the travel time of the slowest trip. C_{bg} correspond to the $PM_{2.5}$ concentration reported by neighboring monitoring sites, and IR_{bg} is assumed to correspond to *Passive* level of physical activity. For D^t and D^L, the total dose inhaled per trip can be recovered simply by multiplying by total time spent in each microenvironment or by total length traveled respectively.

3. Results and discussion

3.1. Physical activity level

For commuters in private cars or taxis, a *Sedentary* level of physical activity was chosen as a result of the accelerometer data (Supplementary Material) and with the literature (Ainsworth et al., 2000). In the case of commuters by bus, since they must walk to the station or bus stop, a *Light* level of physical activity was selected for dose calculations. Commuters in a motorcycle were also assigned a *Light* level of physical activity, consistent with accelerometer data and literature values. For both active modes of transport, a *Moderate* level of physical activity was chosen as explained below.

Physical activity data collected for pedestrians implies an energy expenditure of approximately five METs (see Supplementary Material). Furthermore, the GPS-derived average walking speed for pedestrians on the three road segments averaged between 3.8 and 4.1 km/h. These average speeds includes stops for traffic lights and intersection crossings. According to Ainsworth et al. (2000), walking at that speeds has an associated energy expenditure of 3.3 METs, all this consistent with a *Moderate* level of physical activity.

For cyclists accelerometer data suggests an energy expenditure between 9 and 13 METs, corresponding to a *Vigorous* level of physical activity. However, the GPS-derived average speed for cyclists, between 13 and 14 km/h for all three segments, suggests that the actual energy expenditure is somehow lower, between 4.0 and 6.0 METs (Ainsworth et al., 2000). Furthermore, GPS data shows cyclists spent 18%, 24%, and 20% of the time not moving on Segments 1, 2, and 3 respectively. This observation further supports the choice of a lower level of physical activity. A further look at the frequency distribution of cycling speeds suggest different riding patterns for each of the segments. The first and third quartiles of the distribution for Segment 1 are 10 and 17 km/h respectively. For Segment 2, where the bicyclists have to ride in the traffic lanes, the quartiles are 0 and 24 km/h, suggesting, more frequent stops and a higher riding speed while moving. A similar situation is found for bicyclist in Segment 3 (See Supplementary Material). The choice of *Moderate* level of physical activity for cyclists likely underestimate the actual inhalation rate, and highlights the limitation in the use of categories for this naturally continuous variable. The inhalation rate is likely the largest source of uncertainty in the dose estimates performed in this study.

3.2. Observed PM concentrations

Exposure concentrations measured during the field campaigns were always higher than those reported by the air quality monitoring stations. When PEMs were used to measure $PM_{2.5}$ exposure for pedestrians, the concentrations were 4.5 times higher than reported in site S1. When the DT monitors were used, $PM_{2.5}$ at S1 was 2.8 times higher than roadside measurements (see Supplementary Material). The Pearson correlation coefficient between site S1 and the personal exposure measurements was 0.2, suggesting a poor ability of monitoring sites as indicators of commuters exposure.

The average concentration reported for site S1 was 14.1 $\mu g\ m^{-3}$ during Stage 1, and 20.9 $\mu g\ m^{-3}$ during the Stage 2. The average background inhaled dose per unit time, $C_{bg} \times IR_{bg}$ is then estimated to be 0.07 and 0.10 $\mu g\ min^{-1}$ for Stages 1 and 2 respectively.

Observed time series of PM concentrations for bicyclists and pedestrians were characterized by sudden concentration excursions of a few tens of seconds. The short duration of these elevated exposure concentrations suggest they might be caused by the exhaust plume of a passing vehicle. Geo-located PM concentration measurements for these active modes show that pollution hotspots of *e*BC, $PM_{2.5}$ and N_p are often found when crossing an elevated pedestrian crossing or an underpass. A typical spatial pattern of $PM_{2.5}$ and *e*BC concentration for pedestrians is shown in Fig. 3. In the sample of Fig. 3, peak $PM_{2.5}$ and *e*BC concentrations of up to 735 and 608 $\mu\ gm^{-3}$ respectively were observed.

The characteristic temporal pattern of exposure concentration for travelers in motorized modes indicates that peak concentrations were associated with the periods when the commuter is inside the BRT-bus cabin (Fig. 4). These concentration excursions are often sustained over several minutes, likely due to poor ventilation inside the vehicle cabin. As shown in Fig. 4, $PM_{2.5}$ and *e*BC can remain above 500 $\mu g\ m^{-3}$, and N_p above 200 × 10^3 cm^{-3} over a span of 5 min. A summary of the observations throughout both field campaigns is shown in Fig. 5 and Table 3.

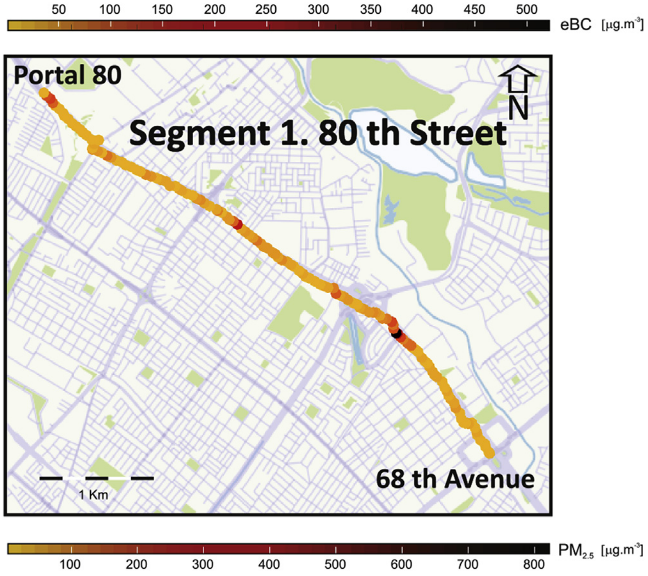

Fig. 3. Spatial distribution of $PM_{2.5}$ and *e*BC for pedestrian commuters on Segment 1. The data was collected on 07/24/2015.

The highest exposure concentrations during the entire campaign were those of BRT system users in Segment 1 (Fig. 5a). Median (mean) concentration for the BRT buses in Segment 1 was 118 (186) $\mu g\ m^{-3}$ of $PM_{2.5}$, 77 (120) $\mu g\ m^{-3}$ of *e*BC, and 194×10^3 (197×10^3) cm^{-3} of N_p. Several factors suggest that these extreme aerosol concentrations are likely influenced not only by the surrounding traffic, but by the emissions of the BRT buses themselves, as has been observed to occur elsewhere (e.g., Marshall and Behrentz, 2005). Although the BRT stations are located in the middle of the 10 traffic lanes, exposure in the stations is nearly 3 times lower than inside the BRT buses, reinforcing the possibility that the extreme concentration inside the BRT buses might be due to self-pollution. In contrast, the lowest average exposure was observed for pedestrians and cyclists also in Segment 1, with concentrations 6 and 6.5 times lower for $PM_{2.5}$ and *e*BC respectively, and nearly 2.5 times lower for N_p compared to the BRT buses.

High concentrations of $PM_{2.5}$, *e*BC, and N_p were observed for all commute modes considered, with the highest concentrations observed in public transport buses. Users of regular Diesel buses in Segments 2 and 3, were exposed to a factor of two higher $PM_{2.5}$ and *e*BC concentrations compared to pedestrians. The concentrations observed in both field campaigns are much higher than reported values in studies performed with similar instruments, particularly for *e*BC. The *e*BC concentration was between 4 and 8 times higher than observed in Barcelona (de Nazelle et al., 2012) and 5 to 10 times higher than Antwerpen (Dons et al., 2012) for pedestrians and cyclists. For bus passengers, the *e*BC exposure is up to 10 times higher than reported in other studies (Karanasiou et al., 2014). In contrast, observed N_p levels in our study are similar to those observed in Barcelona for cyclists and car passengers, but are nearly 4 times higher for bus riders (de Nazelle et al., 2012). N_p levels in our study were consistently higher, by about 5 times, than what has been reported for Basel, Switzerland, with DiSCmini (Ragettli et al., 2013). Observed levels of $PM_{2.5}$ for commuters in bus are two to three times higher than those reported for other Latin American cities, but are similar for cyclists and pedestrians (Suarez et al., 2014). Therefore, although our study shows overall high concentration of N_p, and $PM_{2.5}$, the concentration of *e*BC is extremely high compared when to available literature. This suggests a large contribution from the diesel bus fleet. High correlation was observed between $PM_{2.5}$ and *e*BC throughout the campaign, suggesting that PM is being highly influenced by soot emissions in our measurements.

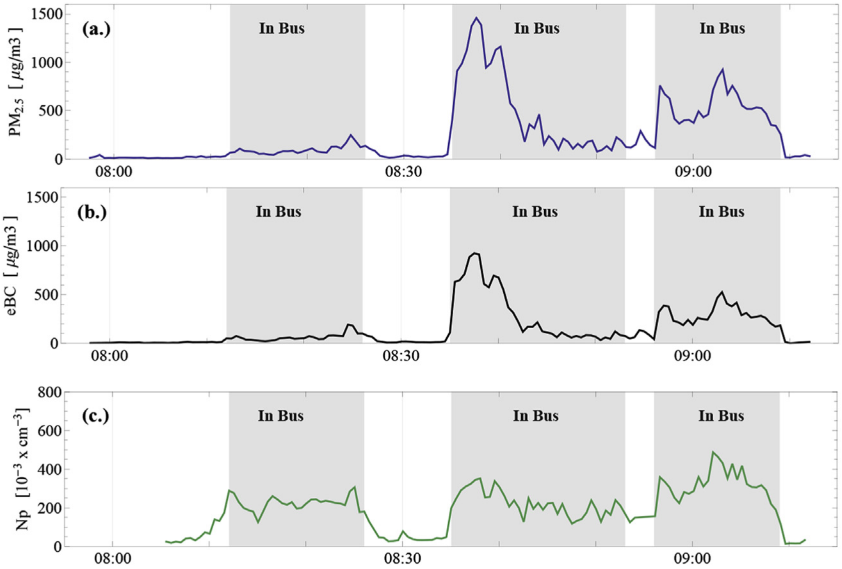

Fig. 4. Particulate matter measurements time series during 07/30/2015 in the BRT system buses on Segment 1. Horizontal axis is local time. (a.) $PM_{2.5}$ concentration ($\mu g\ m^{-3}$), (b.) *e*BC in $\mu g\ m^{-3}$, and (c.) N_p in units of $10^{-3} cm^{-3}$. Gray shading indicates moments were the commuter was traveling inside a BRT-bus. The periods in between shaded regions corresponds to times in which the commuter is inside a BRT station. In this case, the trip was performed three times.

3.3. Exposure and inhaled dose in active vs. motorized modes of transport

Ranking the commute modes in order of decreasing median $PM_{2.5}$ exposure concentration shows a clear split between active and motorized modes (Table 3). The five motorized transport modes rank in the first five positions based either on median $PM_{2.5}$, *e*BC or N_p, irrespective of the road segment traveled. This is consistent with observations reported in other studies. The concentration on the BRT buses on Segment 1, the highest in the entire campaign, are significantly different to all other modes considered, regardless of the street segment. Commuters in private car exhibits the lowest particulate pollution among the motorized modes studied. Furthermore, the car ranked last in inhaled dose in both stages of the campaign, and for all the dose normalizations considered, in a per unit length, per unit time, and total dose. Mean concentrations of $PM_{2.5}$, *e*BC, and N_p inside cars are 2.2, 2.3, and 1.4 times lower than those found on the BRT buses. Across public transportation bus alternatives, hybrid buses cabins exhibit the lowest median $PM_{2.5}$, *eBC*, and N_p. However, these values are not significantly different than those found on traditional diesel buses on the same corridor.

Although commuters in buses and cars were found to be consistently exposed to higher PM concentrations, this is not always the case when dose is calculated. Pedestrians experience a higher $PM_{2.5}$ and *e*BC dose per unit length (Fig. 6 and Table 3) in all streets studied. Furthermore, pedestrians in Segments 2 and 3 have the highest dose per unit length of $PM_{2.5}$ and *e*BC, almost two times higher than pedestrians on Segment 1. The improved ventilation of Segment 1 can explain this large difference. Two main factors contribute to the elevated dose per unit length for pedestrians, namely the longer travel times (three times longer than those of other commute modes) and the elevated inhalation rate. Cyclists, which are exposed to similar particulate concentration as pedestrians, experience lower potential dose per unit length, likely due to the faster travel speed. The dose for bicyclists on Segments 1 and 2 are very similar to the dose for commuters in any of the public transport buses. When dose is calculated in a per unit time basis, pedestrians do not show a statistically different dose to that of bus riders. From the modes considered in our study, only car passengers experience lower dose than the Segment 1 bicyclists.

The $PM_{2.5}$ exposure concentrations and dose observed with the PEMs during Stage 2 of the campaign are consistent with the data collected during Stage 1 despite the different method used. The BRT system buses appear again as the most polluted microenvironment, while pedestrians are exposed to the lowest $PM_{2.5}$ levels. From the point of view of inhaled dose, this data set also place pedestrians as the commuter mode experiencing the larger dose per unit length among all the transport alternatives on Segment 1. $PM_{2.5}$ reported with the PEMs is generally larger than with the DT instruments. Average concentration during Stage 2 was 8 $\mu g\ m^{-3}$ larger than for Stage 1, explaining a fraction of the larger exposure reported in Table 3. However, data reported for Stage 2 of the campaign are average exposure concentrations experienced by commuters from start point to final meeting point, while data reported for Stage 1 includes only measurements collected in the specific microenvironment. Gravimetric measurements yielded consistently higher $PM_{2.5}$ concentration than the photometric method. Since the microenvironments explored are heavily affected by freshly emitted soot particles, it is likely that ultra-fine particles contribute significantly to the aerosol mass concentration. Those particles however, are poorly observed by the DT instrument due to a rapid loss in sensitivity for particle sizes much smaller than a third of the laser wavelength.

3.4. Impact of street configuration and traffic load

Exposure concentration for pedestrians and bicycle users for an open street configuration (Segment 1) was the lowest among the modes surveyed. The difference in exposure concentration with any other mode is statistically significant. The low exposure concentration is in contrast to the high traffic load in this street, which is the highest among the segments considered in our study. The exposure of pedestrians and bike users are essentially identical for this street segment. Two reasons might contribute to these results. First, the open street configuration allows for better ventilation, resulting in lower exposure concentration despite the high emissions from traffic. Second, the exclusive bike lane is built in the

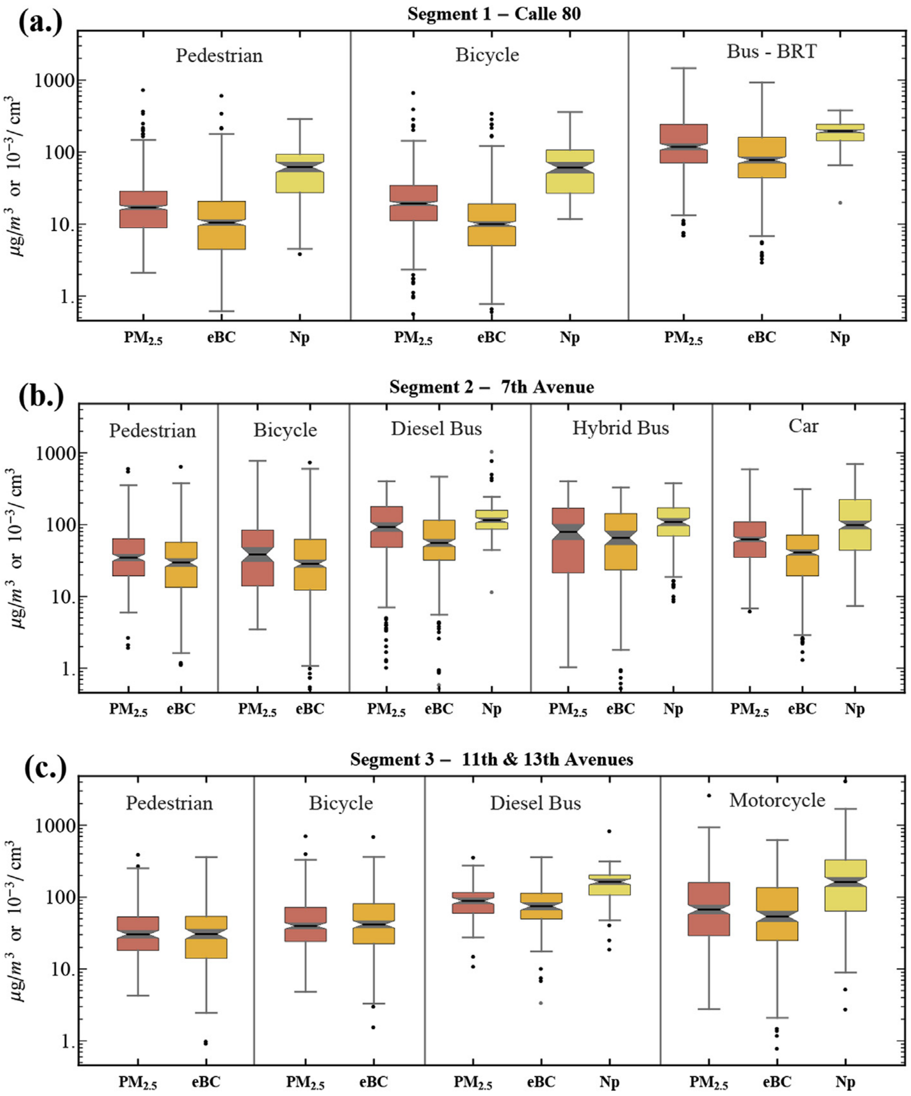

Fig. 5. Distribution of 30-s averages of PM$_{2.5}$, *e*BC (both in units of $\mu g\ m^{-3}$), and *Np* ($10^3 cm^{-3}$) observed during the first stage of the campaign for all the modes surveyed. The box plots notches show confidence intervals for the median. (a.) Segment 1, where measurements were performed for Pedestrians, Cyclists, and BRT system buses. (b.) Segment 2, where the surveyed modes were Pedestrians, Bicycle users, Public Transport Buses, Hybrid Buses of the BRT system, and motorcycle. (c.) Same measurements for Segment 3.

sidewalk, and therefore, pedestrians and bicyclists are both equally distanced from traffic. Three traffic lanes separate the sidewalk from the exclusive BRT lanes (Fig. 2), likely the main source of particulate matter in this street.

For Segments 2 and 3, with a street configuration closer to that of a street canyon, pedestrians and bicycle users were exposed to nearly twice as much PM$_{2.5}$ and *e*BC compared to those in Segment 1. When dose is computed per unit length, pedestrians in Segments 2 and 3 experienced the highest potential PM dose, corresponding to 26.7$\mu g\ km^{-1}$ of PM$_{2.5}$ and 22.0$\mu g\ km^{-1}$ of *e*BC. For a complete trip, this implies a potential dose of up to 126 μg of PM$_{2.5}$ and 103 μg of *e*BC, nearly three times the dose experienced by other commuters. Per unit time, however, the dose experienced by pedestrians is slightly lower than that of bus riders, and almost identical to that of cyclists. Furthermore, the exposure concentration of bike users in Segment 2 was the highest among active modes. The higher exposure of cyclists compared to pedestrians might be explained by the absence of a dedicated bike lane in this corridor, which implies that cyclists must share the mixed traffic lanes. For cyclists in Segment 2, the exposure concentration was on average, 15 $\mu g\ m^{-3}$ higher than exposure for pedestrians in the same street. This is likely due to the fact that cyclists in that segment are forced to share the road with the traffic, highlighting the importance of distance from the sources to reduce exposure.

4. Conclusions

The exposure concentration of fine particulate, black carbon, and the number concentration of particles was measured in different transportation microenvironments in the city of Bogotá, Colombia. The exposure to aerosol was determined for two active transport modes (walking and bicycling) as well as almost the complete offer of motorized transport modes, including public buses, motorcycles, and private vehicles. The travel speed, travel times, and level of physical activity was measured for the various modes considered.

The study found that exposure concentration to PM$_{2.5}$ and *e*BC could be up to 6 times higher in the buses of the BRT system, compared to the concentration exposure of pedestrians and bike users on the same corridor. The BRT system buses were consistently

Table 3
Summary of observations from the measurement campaigns. The statistics reported for the First Stage of the measurements correspond to 30 s averages observations available on each mode. $PM_{2.5}$ concentration reported for the second campaign were collected with Personal Exposure Monitors, and therefore, correspond to average data for the full transect. GSD is the geometric standard deviation, SD is the standard deviation, Q_1 and Q_3 are the values of the first and third quartiles. For the *dose* columns, the number in parenthesis denotes the corresponding rank among the transport modes.

First Stage (07/2015–08/2015)

Mode/Street	$PM_{2.5}$ exposure (DT)		*e*BC exposure		N_p		$PM_{2.5}$ dose			*e*BC dose		Δ*t*
	Median (GSD) μg m^{-3}	Q_1-Q_3	Median (GSD) μg m^{-3}	Q_1-Q_3	Median (GSD) 10^3 cm^{-3}	Q_1-Q_3	$D^L_{i,j}$ μg km^{-1}	$D^t_{i,j}$ μg min^{-1}	$D^{Tot}_{i,j}$ μg	Mean μg km^{-1}	Mean μg min^{-1}	Mean± SD Minutes
BRT-Bus/1 (n = 12)	118.3 (2.5)	71 −242	77.5 (2.8)	44 −161	195 (1.5)	144 −244	(6) 8.2	(1) 2.4	(6) 41.7	(9) 5.3	(2) 1.6	15± 2
Bus/2 (n = 9)	92.9 (3.6)	48 −178	55.8 (3.0)	32 −115	115 (1.7)	87 −158	(5) 8.3	(5) 1.5	(5) 42.7	(7) 5.8	(8) 1.1	26± 9
Bus/3 (n = 6)	88.8 (1.8)	60 −116	74.7 (2.1)	50 −113	164 (1.7)	107 −203	(9) 6.2	(8) 1.3	(9) 34.3	(8) 5.6	(7) 1.2	23± 1
Hybrid-Bus/2 (n = 6)	79.3 (4.3)	21 −170	66.0 (4.4)	23 −143	109 (2.1)	69 −172	(8) 7.4	(7) 1.4	(8) 38.7	(5) 6.3	(6) 1.2	25± 4
Car/2 (n = 6)	62.3 (2.3)	35 −109	41.0 (2.9)	19−72	99 (2.8)	44 −223	(11) 1.8	(11)0.4	(11) 12.8	(11) 1.1	(11) 0.3	19± 6
Bicycle/3 (n = 6)	39.8 (2.3)	24−72	41.7 (2.5)	22−81	–	–	(7) 7.6	(3) 1.7	(7) 41.5	(4) 8.4	(1) 1.9	22± 2
Bicycle/2 (n = 9)	38.4 (3.4)	14−84	28.6 (3.8)	12−63	–	–	(4) 8.3	(2) 2.1	(4) 43.3	(6) 6.1	(3) 1.6	18± 2
Pedestrian/2 (n = 4)	34.8 (2.5)	19−64	29.6 (3.0)	13−57	–	–	(1) 26.7	(4) 1.7	(1) 125.9	(2) 22.0	(5) 1.4	75± 5
Pedestrian/3 (n = 2)	30.4 (2.5)	18−53	30.7 (2.9)	14−54	–	–	(2) 23.0	(6) 1.4	(2) 112.7	(1) 22.9	(4) 1.4	80± 5
Bicycle/1 (n = 12)	19.3 (2.5)	11−34	10.0 (2.8)	5−19	49 (2.4)	23−96	(10) 4.2	(9) 0.9	(10) 23.3	(10) 2.7	(10) 0.5	22± 1
Pedestrian/1 (n = 12)	17.0 (2.4)	9−29	10.5 (3.1)	5−21	49 (2.5)	25−88	(3) 12.5	(10)0.8	(3) 57.1	(3) 9.0	(9) 0.6	68± 6

Second Stage (09/2015–11/2015)

Mode/Street	$PM_{2.5}$ exposure (PEM)		*e*BC exposure		N_p		$PM_{2.5}$ dose			*e*BC dose		Δ*t*
	Median (GSD) μg m^{-3}	Q_1-Q_3	Median (GSD) μg m^{-3}	Q_1-Q_3	Median (GSD) 10^3 cm^{-3}	Q_1-Q_3	$D^L_{i,j}$ μg km^{-1}	$D^t_{i,j}$ μg min^{-1}	$D^{Tot}_{i,j}$ μg	Mean μg km^{-1}	Mean μg min^{-1}	Mean± SD Minutes
BRT-Bus/1 (n = 19)	216.2 (1.3)	176 −255	74.2 (3.7)	20 −114	–	–	(2) 14.3	(1) 2.7	(3) 70.4	(1) 6.5	(1) 1.2	24± 3
Motorcycle/1 (n = 12)	151.0 (1.2)	148 −156	–	–	–	–	(4) 6.9	(4) 2.0	(4) 37.9	–	–	16± 1
Car/1 (n = 19)	131.1 (1.3)	113 −209	–	–	–	–	(5) 3.3	(5) 0.8	(5) 23.2	–	–	18± 3
Bicycle/1 (n = 19)	77.3 (1.5)	77−91	21.0 (2.6)	10−34	–	–	(3) 11.6	(2) 2.7	(2) 73.2	(3) 3.7	(3) 0.8	19± 2
Pedestrian/1 (n = 19)	67.6 (1.4)	56−92	24.4 (3.4)	7−36	–	–	(1) 34.4	(3) 2.2	(1) 167.1	(2) 6.4	(2) 1.0	68± 7

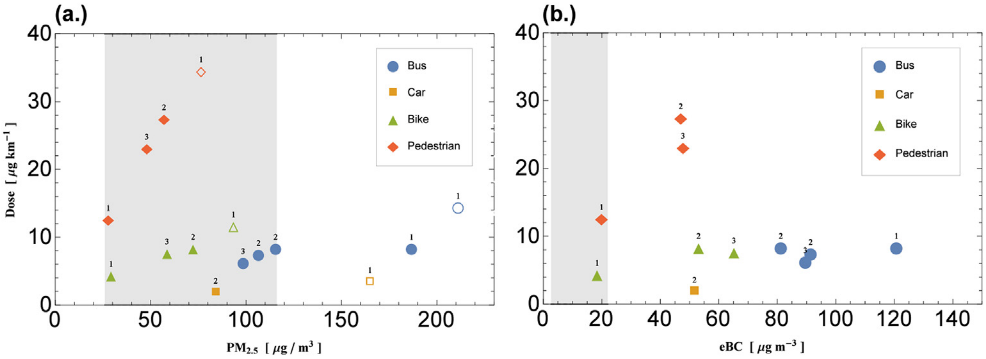

Fig. 6. $PM_{2.5}$ dose per unit length (μg km^{-1}) for commuters in public transport buses, private car or taxi, cyclists, and pedestrians, as function of (a.) $PM_{2.5}$ concentration and (b.) concentration of black carbon. The number on top of the symbols is the corresponding street segment. Open symbols show measurements performed with gravimetric methods during the second stage of the campaign. Shaded region show the range of concentrations reported in other studies using similar instrumentation (Karanasiou et al., 2014).

found to be the most polluted transport microenvironment among the ones considered in the study, as well with the one with the largest inhaled dose per unit time.

Despite the high PM concentrations observed inside the BRT public transport buses, pedestrians were found to experience the high PM potential intake dose. The average dose per unit length for pedestrians was at least 50% higher than for BRT commuters on the same street segment. The lower travel speed and slightly elevated inhalation rates determine the high PM dose for pedestrians. The elevated dose for pedestrians is exacerbated in streets with a street canyon configuration and high traffic volume. The open-street configuration, despite a high traffic load, resulted in low exposures and inhaled dose for pedestrians and cyclists.

The exposure concentration to particulates for commuters in a car was found to be significantly lower than for commuters in other motorized transport modes. The lower exposure combined with relatively short travel times, implies the lowest $PM_{2.5}$ and *e*BC dose for car passengers, compared to all the other transport modes considered. Hybrid and traditional diesel buses, were observed to have similar levels of particulate pollution. The dose experienced by car passengers was found to be the lowest of all modes considered for all metrics considered, per unit time, per unit length basis, and total dose over 80 min.

Extremely high concentrations of equivalent black carbon and sub-micron particle number were observed during the measurement campaigns. Equivalent black carbon is though to contribute a significant fraction of $PM_{2.5}$, implying a large contribution from Diesel engine emissions to the fine particulate concentrations in the city.

The measurements reported in this study could serve to better design the network of dedicated bike-lanes. Bogotá has an extensive network of dedicated bike-lanes, totaling 304 km, and the use of the bicycle as a mode of transport has increased in the last decade, reaching 570 thousand trips a day in 2015. The mobility challenges faced by the city is a common factor to many large urban areas in emerging economies, and implies longer commutes and longer times of exposure to traffic-related pollutants.

Acknowledgments

We acknowledge the contribution of Bogotá Environmental Secretariat personnel, Augusto Molano and Ivan Robayo in data collection. We also acknowledge the participation of Yohen Cuellar, Leidy Tatiana Avila, Diego Miguel Quirama, and the many students who contributed to data collection. This work was partially supported by the Inter-American Development Bank; the Faculty Development Award, from the University of Cincinnati, College of Engineering and Applied Sciences; the *Vicerrectoria de Investigación y Transferencia* of Universidad de la Salle; and by the Department of Civil and Environmental Engineering of Universidad de los Andes. The funding agencies played no role in study design; in the collection, analysis and interpretation of data; or in the writing of the report; and played no role in the decision to submit the work for publication.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.03.006.

References

Ainsworth, B., Haskell, W., Whitt, M., Irwin, M., Swartz, A., Strath, S., O'Brien, W., Bassett, D.R.J., Schmitz, K., Emplaincourt, P., Jacobs, D.R.J., Leon, A., 2000. Compendium of physical activities: an update of activity codes and MET intensities. Med. Sci. Sports Exerc. 32.

Asbach, C., Kaminsky, H., Von Barany, D., Kuhlbusch, T.A., Monz, C., Dziurowitz, N., Pelzer, J., Vossen, K., Berlin, K., Dietrich, S., Götz, U., Kiesling, H.J., Schierl, R., Dahmann, D., 2012. Comparability of portable nanoparticle exposure monitors. Ann. Occup. Hyg. 56, 606–621. http://dx.doi.org/10.1093/annhyg/mes033.

Berghmans, P., Bleux, N., Int Panis, L., Mishra, V., Torfs, R., Van Poppel, M., 2009. Exposure assessment of a cyclist to PM10 and ultrafine particles. Sci. Total Evniron. 407, 1286–1298. http://dx.doi.org/10.1016/j.scitotenv.2008.10.041.

Bigazzi, A.Y., Figliozzi, M.A., 2014. Review of urban bicyclists' intake and uptake of traffic-related air pollution. Transp. Rev. 34, 221–245. http://dx.doi.org/10.1080/01441647.2014.897772.

Boogaard, H., Borgman, F., Kamminga, J., Hoek, G., 2009. Exposure to ultrafine and fine particles and noise during cycling and riving in 11 Dutch cities. Atm. Env. 43, 4234–4242. http://dx.doi.org/10.1016/j.atmosenv.2009.05.035.

Both, A.F., Westerdahl, D., Fruin, S., Haryanto, B., Marshall, J.D., 2013. Exposure to carbon monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: effect of commute mode. Sci. Total Environ. 443, 965–972. http://dx.doi.org/10.1016/j.scitotenv.2012.10.082.

Cepeda, M., Schoufour, J., Freak-Poli, R., Koolhaas, C.M., Dhana, K., Bramer, W.M., Franco, O.H., 2016. Levels of Ambient Air Pollution According to Mode of Transport: a Systematic Review. The Lancet Public Health. http://dx.doi.org/10.1016/S2468-2667(16)30021-4.

Cheng, Y.H., Lin, M.H., 2013. Real-time performance of the micro-aeth AE51 and the effects of aerosol loading on its measurement results at a traffic site. Aerosol Air Qual. Res. 13, 1853–1863. http://dx.doi.org/10.4209/aaqr.2012.12.0371.

Cole-Hunter, T., Morawska, L., Stewart, I., Jayaratne, R., Solomon, C., 2012. Inhaled particle counts on bicycle commute routes of low and high proximity to motorised traffic. Atmos. Environ. 61, 197–203. http://dx.doi.org/10.1016/j.atmosenv.2012.06.041.

Do, D.H., Van Langenhove, H., Chigbo, S.I., Amare, A.N., Demeestere, K., Walgraeve, C., 2014. Exposure to volatile organic compounds: comparison among different transportation modes. Atmos. Environ. 94, 53–62. http://dx.doi.org/10.1016/j.atmosenv.2014.05.019.

Dons, E., Int Panis, L., Van Poppel, M., Theunis, J., Wets, G., 2012. Personal exposure to black carbon in transport microenvironments. Atmos. Environ. 55, 392–398. http://dx.doi.org/10.1016/j.atmosenv.2012.03.020.

Fajardo, O.A., Rojas, N.Y., 2012. Particulate matter exposure of bicycle path users in a high-altitude city. Atmos. Environ. 46, 675–679. http://dx.doi.org/10.1016/j.atmosenv.2011.09.047.

Fernandez-Bremauntz, A., Ashmore, M., 1995. Exposure of commuters to carbon monoxide in Mexico City I. measurement of in-vehicle concentrations. Atmos. Environ. 29, 525–532.

Fierz, M., Houle, C., Steigmeier, P., Burtscher, H., 2011. Design, calibration, and field performance of a miniature diffusion size classifier. Aerosol Sci. Tech. 45, 1–10. http://dx.doi.org/10.1080/02786826.2010.516283.

Franco, J.F., Segura, J.F., Mura, I., 2016. Air pollution alongside bike-paths in bogotá-Colombia. Front. Environ. Sci. 4, 77. http://dx.doi.org/10.3389/fenvs.2016.00077.

Freedson, P.S., Melanson, E., Sirard, J., 1998. Calibration of the computer science and applications, Inc. accelerometer. Med. Sci. Sports Exerc. 30, 777–781.

Gulliver, J., Briggs, D., 2004. Personal exposure to particulate air pollution in transport microenvironments. Atmos. Environ. 38, 1–8. http://dx.doi.org/10.1016/j.atmosenv.2003.09.036.

Hankey, S., Marshall, J.D., 2015. On-bicycle exposure to particulate air pollution: particle number, Black Carbon, $PM_{2.5}$, and particle size. Atmos. Environ. 122, 65–73. http://dx.doi.org/10.1016/j.atmosenv.2015.09.025.

Hertel, O., Hvidberg, M., Ketzel, M., Storm, L., Stausgaard, L., 2008. A proper choice of route significantly reduces air pollution exposure: a study on bicycle and bus trips in urban streets. Sci. Total Evniron 389, 58–70. http://dx.doi.org/10.1016/j.scitotenv.2007.08.058.

Huang, J., Deng, F., Wu, S., Guo, X., 2012. Comparisons of personal exposure to $PM_{2.5}$ and CO by different commuting modes in Beijing, China. Sci. Total Evniron. 425, 52–59. http://dx.doi.org/10.1016/j.scitotenv.2012.03.007.

Int Panis, L., de Geus, B., Vandenbulcke, G., Willems, H., Degraeuwe, B., Bleux, N., Mishra, V., Thomas, I., Meeusen, R., 2010. Exposure to particulate matter in traffic: a comparison of cyclists and car passengers. Atmos. Environ. 44, 2263–2270. http://dx.doi.org/10.1016/j.atmosenv.2010.04.28.

Karanasiou, A., Viana, M., Querol, X., Moreno, T., de Leeuw, F., 2014. Assessment of personal exposure to particulate air pollution during commuting in European cities: recommendations and policy implications. Sci. Total Environ. 490, 4781–4810. http://dx.doi.org/10.1016/j.scitotenv.2014.05.036.

Kaur, S., Nieuwenhuijsen, M., Colvile, R., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmos. Environ. 41, 4781–4810. http://dx.doi.org/10.1016/j.atmosenv.2007.02.002.

Kawahara, J., Tanaka, S., Tanaka, C., Aoki, Y., Yonemoto, J., 2011. Estimation of daily inhalation rate in preschool children using a tri-axial accelerometer: a pilot study. Sci. Total Environ. 409, 3073–3077. http://dx.doi.org/10.1016/j.scitotenv.2011.04.006.

Kingham, S., Longley, I., Salmond, J., Pattinson, W., Shrestha, K., 2013. Variations in exposure to traffic pollution while travelling by different modes in a low density, less congested city. Environ. Pollut. 181, 211–218. http://dx.doi.org/10.1016/j.envpol.2013.06.030.

Krzyżanowski, M., Kuna-Dibbert, B., Schneider, J., 2005. Health Effects of Transport-related Air Pollution. WHO Regional Office Europe.

Li, B., ning Lei, X., li Xiu, G., yuan Gao, C., Gao, S., sheng Qian, N., 2015. Personal exposure to Black Carbon during commuting in peak and off-peak hours in Shanghai. Sci. Total Environ. 524–525, 237–245. http://dx.doi.org/10.1016/j.scitotenv.2015.03.088.

Liu, W.T., Ma, C.M., Liu, I.J., Han, B.C., Chuang, H.C., Chuang, K.J., 2015. Effects of commuting mode on air pollution exposure and cardiovascular health among young adults in Taipei, Taiwan. Int. J. Hyg. Environ. Health 218, 319–323. http://dx.doi.org/10.1016/j.ijheh.2015.01.003.

Marshall, J.D., Behrentz, E., 2005. Vehicle self-pollution intake fraction: children's exposure to school bus emissions. Environ. Sci. Technol. 39, 2559–2563. http://dx.doi.org/10.1021/es040377v pMID: 15884349.

Meier, R., Clark, K., Riediker, K., 2013. Comparative testing of a miniature diffusion size classifier to assess airborne ultrafine particles under field conditions. Aerosol Sci. Tech. 47, 22–28. http://dx.doi.org/10.1080/02786826.2012.720397.

Michaels, R.A., Kleinman, M.T., 2000. Incidence and apparent health significance of brief airborne particle excursions. Aerosol Sci. Technol. 32, 93–105. http://dx.doi.org/10.1080/027868200303803.

Moraes, R.H., Schwanen, T., 2015. Commute Time in Brazil (1992-2009): Differences between Metropolitan Areas, by Income Levels and Gender (Discussion Paper).

de Nazelle, A., Scott, F., Dan, W., Martinez, D., Ripoll, A., Nadine, K., Nieuwenhuijsen, M., 2012. A travel mode comparison of commuters' exposures to air pollutants in barcelona. Atmos. Environ. 59, 151–159. http://dx.doi.org/10.1016/j.atmosenv.2012.05.013.

Nyhan, M., McNabola, A., Misstear, B., 2014. Comparison of particulate matter dose and acute heart rate variability response in cyclists, pedestrians, bus and train passengers. Sci. Total Environ. 468–469, 821–831. http://dx.doi.org/10.1016/j.scitotenv.2013.08.096.

Pope III, C., Dockery, D.W., Spengler, J.D., Raizenne, M.E., 1991. Respiratory health and PM_{10} pollution: a daily time series analysis. Am. Rev. Respir. Dis. 144, 668–674.

Ragettli, M.S., Corradi, E., Braun-Fahrländer, C., Schindler, C., de Nazelle, A., Jerrett, M., Ducret-Stich, R.E., Künzli, N., Phuleria, H.C., 2013. Commuter exposure to ultrafine particles in different urban locations, transportation modes and routes. Atmos. Environ. 77, 376–384. http://dx.doi.org/10.1016/j.atmosenv.2013.05.003.

Ramos, M.J., Vasconcelos, A., Faria, M., 2015. Comparison of particulate matter inhalation for users of different transport modes in Lisbon. Transp. Res. Procedia 10, 433–442. http://dx.doi.org/10.1016/j.trpro.2015.09.093, 18th Euro Working Group on Transportation, EWGT 2015, 14-16 July 2015, Delft, The Netherlands.

Sarnat, J.A., Golan, R., Greenwald, R., Raysoni, A.U., Kewada, P., Winquist, A., Sarnat, S.E., Flanders, W.D., Mirabelli, M.C., Zora, J.E., Bergin, M.H., Yip, F., 2014. Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. Environ. Res. 133, 66–76. http://dx.doi.org/10.1016/j.envres.2014.05.004.

Suarez, L., Mesias, S., Iglesias, V., Silva, C., Caceres, D.D., Ruiz-Rudolph, P., 2014. Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. Environ. Sci. Process. Impacts 16, 1309–1317. http://dx.doi.org/10.1039/C3EM00648D.

US-EPA, 2011. Exposure Factors Handbook, 2011 Edition (Final), EPA/600/R-09/052. United States Environmental Protection Agency.

Virkkula, A., Chi, X., Ding, A., Shen, Y., Nie, W., Qi, X., Zheng, L., Huang, X., Xie, Y., Wang, J., Petäjä, T., Kulmala, M., 2015. On the interpretation of the loading correction of the aethalometer. Atmos. Meas. Tech. Discuss. 8, 7373–7411.

Virkkula, A., Mäkelä, T., Hillamo, R., Yli-Tuomi, T., Hirsikko, A., Hämeri, K., Koponen, I., 2007. A simple procedure for correcting loading effects of Aethalometer data. J. Air & Waste Manage. Assoc. 57, 1214–1222. http://dx.doi.org/10.3155/1047-3289.57.10.1214.

Xie, X., Huang, Z., Wang, J., 2006. The impact of urban street layout on local atmospheric environment. Build. Environ. 41, 1352–1363. http://dx.doi.org/10.1016/j.buildenv.2005.05.028.

Yang, F., Kaul, D., Wong, K.C., Westerdahl, D., Sun, L., Ho, K.f., Tian, L., Brimblecombe, P., Ning, Z., 2015. Heterogeneity of passenger exposure to air pollutants in public transport microenvironments. Atmos. Environ. 109, 42–51. http://dx.doi.org/10.1016/j.atmosenv.2015.03.009.

Zhang, Y., Beenakker, K.G.M., Butala, P.M., Lin, C.C., Little, T.D.C., Maier, A.B., Stijntjes, M., Vartanian, R., Wagenaar, R.C., 2012. Monitoring walking and cycling of middle-aged to older community dwellers using wireless wearable accelerometers, in: 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 158–161. doi:10.1109/EMBC.2012.6345895.

Zuurbier, M., Hoek, G., Oldenwening, M., Lenters, V., Meliefste, K., van den Hazel, P., Brunekreef, B., 2010. Exposure to particulate matter in traffic: a comparison of cyclists and car passengers. Environ. Health Perspect. 118, 783–789. http://dx.doi.org/10.1016/j.atmosenv.2010.04.28.