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

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## 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.

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## 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

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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