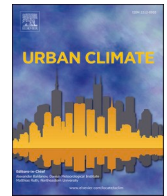




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Urban cycling and air quality: Characterizing cyclist exposure to particulate-related pollution

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ABSTRACT

Bogotá is a leading city with regard to urban cycling infrastructure in Latin America. This study evaluated cyclist exposure to particle-related air pollution on selected bicycle lanes in Bogotá. We provide new data on cyclist inhalation rates and the chemical composition of ambient particulate matter. We measured real-time concentrations of particulate matter (PM_{2.5}) and black carbon (BC) on two different bicycle lanes. Cyclist exposure to PM_{2.5} and BC ranged between 10.5 and 36.0 µg/m³ and 4.5 and 7.9 µg/m³, respectively. The highest exposure was measured on bicycle lanes adjacent to roads with major vehicular traffic. We also measured PM_{2.5} concentrations by a gravimetric method using a fixed monitoring point located in one of the bicycle stretches. The chemical composition of PM_{2.5} showed high concentrations of Ca, Fe, Al, and Mg, with mean values ranging from 63 ng/m³ to 286 ng/m³. The detected trace elements were Cu, Zn, and Ba at concentrations exceeding 10 ng/m³. Our results highlight the influence of traffic emissions (direct emissions and PM resuspension) on cyclist exposure to hazardous air pollutants (such as PM_{2.5} and BC). Our findings emphasize the need to consider air quality in the urban planning and implementing of cycling infrastructure.

1. Introduction

Air pollution is a major ambient risk factor for human health (HEI, 2019). Exposure to air pollutants causes 4.2 million premature deaths per year worldwide (WHO, 2018). High exposure to particulate matter (PM) is associated with respiratory and cardiovascular morbidity (Song et al., 2014; Krall et al., 2018), strokes (Villeneuve et al., 2006), asthma (Fan et al., 2015), adverse birth outcomes (Arroyo et al., 2016), cognitive effects, and dementia (Baumgart et al., 2015; Chen et al., 2017). In urban microenvironments, research has focused on PM_{2.5} (PM <2.5 µm in aerodynamic diameter) and the associated black carbon (BC) fraction due to their small size and adverse effects on human health (WHO, 2012; Kim et al., 2015). BC is recognized as a diesel vehicle emissions tracer (Fruin et al., 2004; Targino et al., 2016) and is a short-lived climate pollutant.

Poor urban air quality has contributed to the replacement of motorized travel by active modes of travel, such as cycling (Pratt et al.,

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Table 1
Main features of the studied bicycle paths.

| Stretch | Section | Length (km) | Configuration street/bicycle path ^a | # traffic lanes | Distance to traffic lanes (m) | Vehicular flow (#/h) | | | | | | | | | | | | | | | |
|-----------------|----------|-------------|--|-----------------|-------------------------------|----------------------|------------|-----|-------|-------|---------------|------------|-----|-------|-------|------------|------------|-----|-------|-------|--|
| | | | | | | Weekdays | | | | | | | | | | Weekends | | | | | |
| | | | | | | Rush hour | | | | | Non-rush hour | | | | | | | | | | |
| | | | | | | Automobile | Motorcycle | Bus | Truck | Total | Automobile | Motorcycle | Bus | Truck | Total | Automobile | Motorcycle | Bus | Truck | Total | |
| A (Central) | Southern | 3.1 | Open Street OSL bicycle path | 12 | 1.5–4 | 1336 | 900 | 340 | 180 | 2756 | 2072 | 924 | 276 | 172 | 3444 | NA | NA | NA | NA | NA | |
| | Central | 2.0 | Open Street OSL bicycle path | 5 | 1.5 | 1636 | 664 | 44 | 72 | 2416 | 2312 | 476 | 32 | 80 | 2900 | 332 | 52 | 16 | 12 | 412 | |
| | | | CBL | 5 | < 1 | | | | | | | | | | | | | | | | |
| | Eastern | 1.9 | Closed Street Sh | 2 4 | 0 | 1200 | 452 | 24 | 108 | 1784 | 648 | 108 | 24 | 32 | 812 | NA | NA | NA | NA | NA | |
| | | | | | Total | 4172 | | 408 | 360 | 6956 | 5032 | 1508 | 332 | 284 | 7156 | 332 | 52 | 16 | 12 | 412 | |
| B (Northern) | Eastern | 4.2 | Closed Street OSL bicycle path | 3 | 1.5 | 864 | 352 | 176 | 32 | 1424 | 1048 | 332 | 140 | 48 | 1568 | NA | NA | NA | NA | NA | |
| | | | CBL | 3 | < 1 | | | | | | | | | | | | | | | | |
| | Central | 1.0 | Open Street OSL bicycle path | 8 | 1–4 | 792 | 332 | 56 | 20 | 1200 | 728 | 332 | 68 | 8 | 1136 | 496 | 48 | 44 | 4 | 592 | |
| | Northern | 1.8 | Closed Street COS bicycle path | 4 | 4–5 | 1012 | 324 | 28 | 44 | 1408 | 1028 | 284 | 32 | 32 | 1376 | NA | NA | NA | NA | NA | |
| | | | | | Total | 2668 | 1008 | 260 | 96 | 4032 | 2804 | 948 | 240 | 88 | 4080 | 496 | 48 | 44 | 4 | 592 | |

NA: Not available (no data or no video available).

^a OSL: Off-street lateral, CBL: Central bicycle lane, Sh: Shared lines, COS: Central off-street.

2012). This strategy has been widely accepted by several cities due to decrease congestion (Médard de Chardon, 2019) and the many positive effects of physical activity on health (Saunders et al., 2013). However, cycling infrastructure next to roads has been recognized as a risky scenario for cyclists due to air pollutants exposure (Bigazzi and Figliozzi, 2014). Although this has attracted the attention of the scientific community (de Nazelle et al., 2017), there are few studies carried out in Latin American cities where many people are exposed constantly to PM coming from anthropogenic sources, such as vehicular traffic (Green and Sánchez, 2013; Hérick et al., 2016).

Bogotá is the capital of Colombia and one of the largest cities in Latin America. As with other cities in the region, Bogotá has high vehicular congestion and low air quality (Zhu et al., 2012; UNEP, 2016; Ramírez et al., 2018a; Mura et al., 2020). High emissions from heavy vehicles and motorcycles typically occur in urban areas. Official emissions inventories indicate that mobile sources in the city represent approximately 60% of the total PM (SDA, 2009; Pachón, 2018), with diesel vehicles accounting for more than 70% of these emissions (despite being less than 5% of the total car fleet) (Pachón, 2018; Ramírez et al., 2018b; SDM, 2019b).

In response to the traffic congestion problems, local authorities in Bogotá have implemented several sustainable mobility strategies (e.g., increasing mass public transport lines and building cycling infrastructure) (Gonzalez et al., 2020). The city, with one of the largest bicycle infrastructures in Latin America, has more than 530 km of bicycle paths (BID, 2015) and approximately 635 thousand bicycle trips per day (5% of total daily trips) (SDM, 2018; SDM, 2019c). However, most of the dedicated bicycle lanes are adjacent to roads with high vehicular traffic; this poses a serious health risk to cyclists considering their high pollutant intake due to increased ventilation rates (VR; Zuurbier et al., 2010; Ham et al., 2017) and high levels of physical activity (Bigazzi and Figliozzi, 2014; Park et al., 2017).

Measurements of PM₁₀ (PM <10 µm in aerodynamic diameter) exposure levels at two fixed sites on a bicycle path in the west of the city indicated mean concentrations of 77.9–108.0 µg/m³ (Fajardo and Rojas, 2012). Moreover, Franco et al. (2016) identified mean PM_{2.5} and BC concentrations of 30–136 µg/m³ and 10–38 µg/m³, respectively, on four bicycle paths in the north and west of the city. Morales et al. (2017) determined that cyclists inhaled a higher fraction of fine PM_{2.5} particles and BC than drivers of motorized transport modes.

Despite the preliminary evidence, local authorities in Bogotá and other Colombian cities do not consider air quality impacts when designing and preconstructing cycling infrastructure. Therefore, it is necessary to obtain further scientific evidence to characterize better air pollution exposure on cyclists in dedicated bicycle lanes adjacent to major urban roads. The objective of this study was to characterize the exposure of urban cyclists to air pollution in Bogotá by providing new data on the intake dose and ambient PM chemical composition. We also highlighted the impacts of mobile sources on air quality in the vicinity of dedicated bicycle lanes in the city.

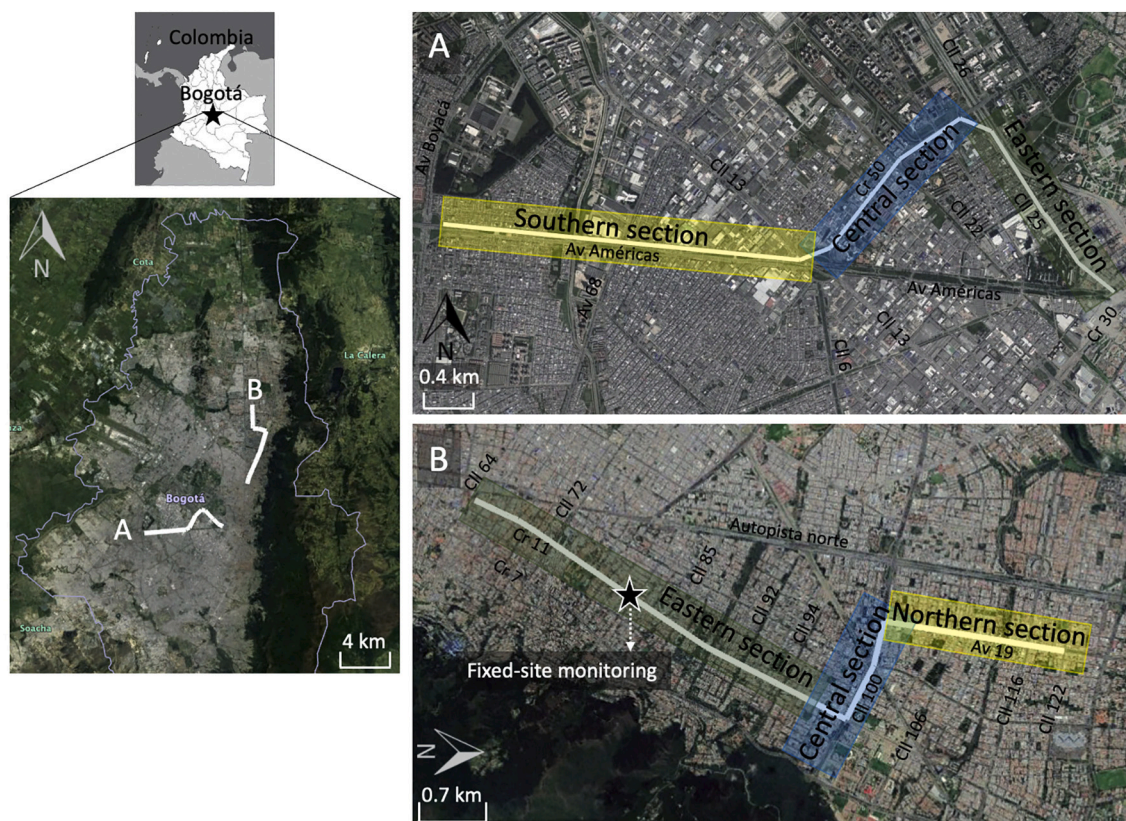


Fig. 1. Bicycle path stretches evaluated during the mobile campaign. Images obtained from Google Earth (<https://www.google.com/earth/>).

2. Material and methods

2.1. Study area

Bogotá is located in the Andes mountain range (2640 m above sea level [m.a.s.l]) in the central region of Colombia. It has a mean annual temperature of 14 °C and two rainy seasons throughout the year (April–May and October–November) (IDEAM, 2015). The city has a population of approximately eight million inhabitants, with a density of 21,000 inhabitants/km² (DANE, 2010; SDM, 2018). Bogotá's citizens undertake more than 13 million trips a day, with 45% of trips related to buses of the public transport system, 18% related to private cars and taxis, 5% related to motorcycles, and 26% related to active transport such as walking and cycling (SDM, 2018). The bus fleet providing the public transport service has an average age of 21 years (DNP, 2018); buses are therefore a major source of air pollution due to the absence of modern emission control systems. A total of 635,000 daily bicycle trips have been registered in Bogotá, 30% of which are work commutes (SDM, 2018). Moreover, 53% of trips are undertaken by people between 26 and 45 years old (SDM, 2018), and the average distance per bicycle round trip is 7 km (SDM, 2013).

2.2. Mobile campaign

Two 7-km stretches of dedicated bicycle lanes were selected for this study (see Table 1). Stretch A extends from the intersection of Avenida Américas and Avenida Boyacá to Carrera 30a and Calle 25 (Fig. 1A). The stretch is located in the geographical center of the city and covers residential, commercial, and industrial areas (locality of Puente Aranda between Carrera 50 and Avenida 68 on Avenida Américas). Avenida Américas on Stretch A is relatively wide (approximately 90 m) and includes two lanes for the bus rapid transit system (Transmilenio). Diesel vehicles—such as heavy-duty vehicles and inter-municipal buses—also use this avenue.

Stretch B extends from Calle 64 and Carrera 11 to Avenida 19 and Calle 122 (Fig. 1B). The stretch is located in northeast Bogotá and covers commercial and residential areas. An important feature of this section is the narrow configuration of Carrera 11 (approximately 10 m) and the high transit of buses and motorcycles.

Both stretches are of high importance to users and have different bicycle path compositions; these include off-street bicycle paths (bicycle paths on sidewalks), bicycle lanes (exclusive lanes for bicycles on the road), and shared lanes (lanes with mixed vehicle and bicycle use). Each stretch was divided into three study sections with particular characteristics (Table 1). Field video analysis was conducted to obtain weekday and weekend vehicular flows for each stretch.

The PM_{2.5} concentrations were measured using a DustTrak II model 8530 (TSI Incorporated, USA) with a flow rate of 3 L/min and a temporal resolution of 30 s. DustTrak data often overestimate PM_{2.5} concentrations due to mass median diameters – particle size, morphology, and composition of urban aerosols that differ from polydisperse aerosol. Therefore, measurements are divided by correction factors between 1.70 and 2.78, typically applied to urban (McNamara et al., 2011; Wallace et al., 2011). In this study, we did not perform gravimetric measurements during sampling, and a specific correction factor for the measurements was not obtained. However, a correction factor of 2 was applied to all PM_{2.5} data, based on Targino et al. (2016).

The BC concentrations were measured using a portable aethalometer model AE51 (AethLabs, USA) operating at a wavelength of 880 nm. A flow rate of 100 mL/min and a temporal resolution of 30 s were set as operative conditions. Several correction equations have been proposed to correct aethalometer measurements for the filter loading effect (Kirchstetter and Novakov, 2007; Virkkula et al., 2007; Good et al., 2016). In this study, we used the correction reported by Kirchstetter and Novakov (2007) to adjust the BC values. The data used to analyze BC concentrations were related to a filter with a light attenuation (Δ ATN) of less than 120.

Following Franco et al. (2016), Hofman et al. (2018), and Targino et al. (2018), students from the Environmental Engineering program at Universidad EAN carried the equipment on their bicycles for each experiment. The equipment was attached to the front of each bicycle, allowing for the sampling lines to capture pollutants without any obstruction; the equipment was also supported at the bottom to avoid vibration. Round trips were conducted in the morning and included rush hours (RH) (6:00–8:30 h) and non-rush hours (NORH) (9:00–11:00 h), and the students traveled a total of 14 km per day in each stretch. Sampling was conducted three times during weekdays and twice during weekends.

The field measurements were conducted during a dry period between August 22 and September 24, 2017, to avoid the influence of rainfall on pollutant concentrations. Georeferenced data were obtained from the Strava App at a time resolution of 1 s. This app was selected because it is popular with cyclists in Bogotá and has been used in previous studies (Sun et al., 2017; Brand et al., 2019).

2.3. Fixed-site monitoring

We collected PM_{2.5} filter samples at a fixed point at the Eastern section of Stretch B (Carrera 11 and Calle 79–04°39'48.44" N; 74°03'16.74" W) (Fig. 1B). The site is influenced by traffic on Carrera 11 and represents a typical busy urban street in Bogotá. A Hi-Vol model TE-6001-2.5 (Tisch Environmental Inc., USA) air sampler was placed 2 m from the bicycle path (type off-street lateral bicycle lane) at ground level to measure the air quality (PM_{2.5} concentrations) in a busy cycling section.

The PM_{2.5} measurements in this study followed the United States reference method CFR 40 Part 50 Appendix J, which is incorporated in Colombia's regulation (MAVDT, 2008). Whatman quartz fiber filters (203 mm × 254 mm) were previously conditioned at a constant temperature (20 ± 5 °C) and relative humidity (50 ± 5%). A flow rate of 1110 ± 0.003 m³/min was monitored, and the parameter was corrected to reference conditions (760 mmHg and 25 °C) using Eq. (1) (Bravo et al., 2013):

$$Q_{std} = Q_a \times \left(\frac{P_{av}}{T_{av}} \right) \times \left(\frac{T_{std}}{P_{std}} \right) \quad (1)$$

where Q_{std} is the mean flow rate under reference conditions, Q_a is the mean flow rate under ambient conditions, P_{av} is the mean barometric pressure during the sampling period, T_{av} is the mean ambient temperature during the sampling period, T_{std} is the standard temperature, and P_{std} is the standard pressure. The barometric pressure and ambient temperature were obtained from the nearest Air Quality Monitoring Network station, the Las Ferias station. The study was conducted during a dry period, and the mean temperature and barometric pressure during 12-h sampling time (from 7:00 am to 7:00 pm) were 14.5 ± 3.3 °C and 752.9 ± 1.3 hPa, respectively, based on hourly values.

The samples were collected over two weekdays and Sundays between August 23 and September 10, 2017. A total of eight valid samples were obtained (six weekday samples and two Sunday samples).

2.4. Chemical composition of $PM_{2.5}$

After gravimetric analysis, the filters were sent to the Wisconsin State Laboratory of Hygiene (University of Wisconsin-Madison, USA) for the characterization of mineral and metallic elements, including Ca, Fe, Al, Mg, Cu, Zn, Ba, Mn, Pb, Sr, Cr, Sb, Sn, Ni, V, As, Cd, and Co.

The $PM_{2.5}$ filter samples were acid digested (6 mL HNO_3 + 3 mL HCl) using a PRO24 Microwave Rotor system. The residue was recovered in a Milli-Q water solution and diluted to 30 mL. Subsequently, the elements were quantified using a sector field (magnetic sector) inductively coupled plasma mass spectrometer (SF-ICPMS; Thermo Finnigan Element 2 mass spectrometer, Thermo Scientific, USA; Okuda et al., 2014). The QA/QC samples included sample and Milli-Q spikes, replicates, and filter blanks, and primary and secondary standard checks were carried out.

2.5. Inhalation rate

We used the model equation by Do Vale et al. (2015) to establish cyclist VR (in L/min) (Eq. (2)). For biological variables, a qualified physician trained the project assistants to use a pulse oximeter with a digital heart rate monitor (heart rate [HR]/min) to detect vital signs.

$$VR = 0.00070724 \times HR^{2.17008537} \quad (2)$$

To evaluate the concentrations of contaminants affecting cyclists, we calculated the $PM_{2.5}$ inhalation rate for each stretch using Eq. (3) (Do Vale et al., 2015), assuming a duration of 2 h for one complete route (round trip):

$$PM_{inh} = PM_{conc} \times VR \times t \quad (3)$$

where PM_{inh} (μg) is the mass of pollutants entering the respiratory tract of cyclists throughout the route (round trip); PM_{conc} ($\mu\text{g}/\text{m}^3$) is the median pollutant ($PM_{2.5}$) exposure recorded at each stretch, which was discriminated by RH and NORH and by weekdays and weekends; VR (m^3/min) is the pulmonary ventilation rate; and t (min) is the total travel time for each stretch (round trip) or stretch section.

3. Results and discussion

3.1. $PM_{2.5}$ and BC concentrations

Table 2 shows the median and interquartile range (due to nonparametric distribution) of the $PM_{2.5}$ and BC concentrations for the two studied stretches under different monitoring conditions. The concentration data are presented in Fig. 2.

The median $PM_{2.5}$ and BC concentrations (using the 30-s data) were 23.0–48.5 $\mu\text{g}/\text{m}^3$ and 6.1–7.5 $\mu\text{g}/\text{m}^3$ in Stretch A, respectively, and 7.0–14.0 $\mu\text{g}/\text{m}^3$ and 3.6–6.9 $\mu\text{g}/\text{m}^3$ in Stretch B, respectively (Table 2). The median $PM_{2.5}$ concentration in Stretch A was three times that of Stretch B, while BC concentrations were 1.7 times higher in Stretch A than Stretch B. These differences are likely related to the individual characteristics of each stretch, including traffic composition; for example, 60% more cars, motorcycles, and

Table 2

Concentrations of $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) and BC ($\mu\text{g}/\text{m}^3$) during rush hour (RH), non-rush hour (NORH), and weekends (Sunday).

| Stretch | RH | | | | NORH | | | | Weekend (Sunday) | | | |
|---------|--------------------|------|-------------------|------|-------------------|------|------------------|-----|-------------------|------|------------------|-----|
| | $PM_{2.5}$ | IQR | BC | IQR | $PM_{2.5}$ | IQR | BC | IQR | $PM_{2.5}$ | IQR | BC | IQR |
| A | $n = 762$ 48.5 | 31.4 | $n = 902$ 10.2 | 12.0 | $n = 861$ 23.0 | 30.5 | $n = 799$ 6.1 | 7.5 | $n = 491$ 17.5 | 22.0 | $n = 391$ 4.3 | 5.4 |
| B | $n = 1399$ 14.0 | 21.5 | $n = 1165$ 5.3 | 8.7 | $n = 1171$ 7.0 | 12.5 | $n = 945$ 3.6 | 6.9 | $n = 330$ 4.5 | 8.5 | $n = 439$ 1.1 | 2.1 |

IQR: Interquartile range.

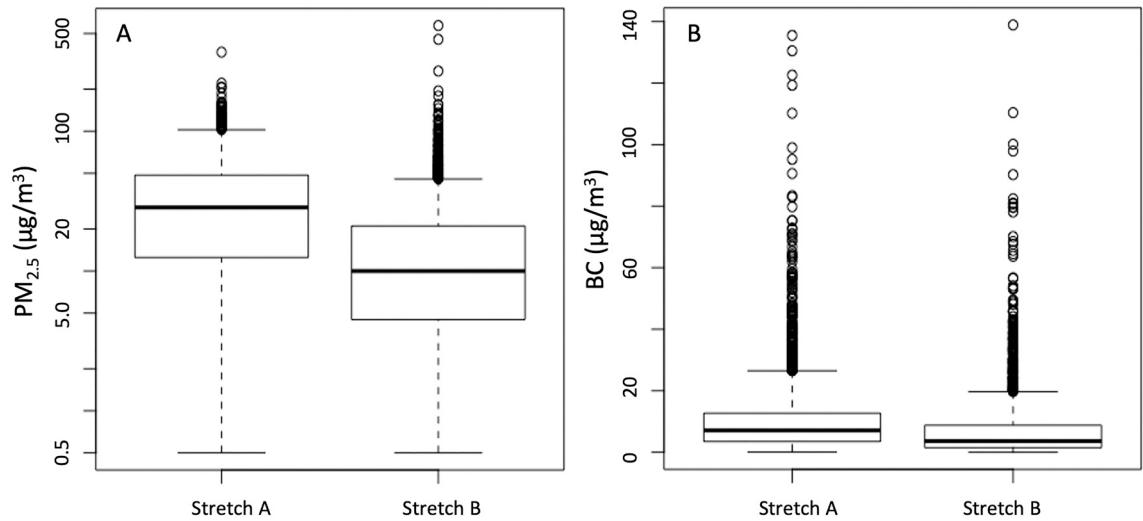


Fig. 2. Concentration of (A) $PM_{2.5}$ and (B) BC considering all data ($t = 30$ s) for Stretches A and B.

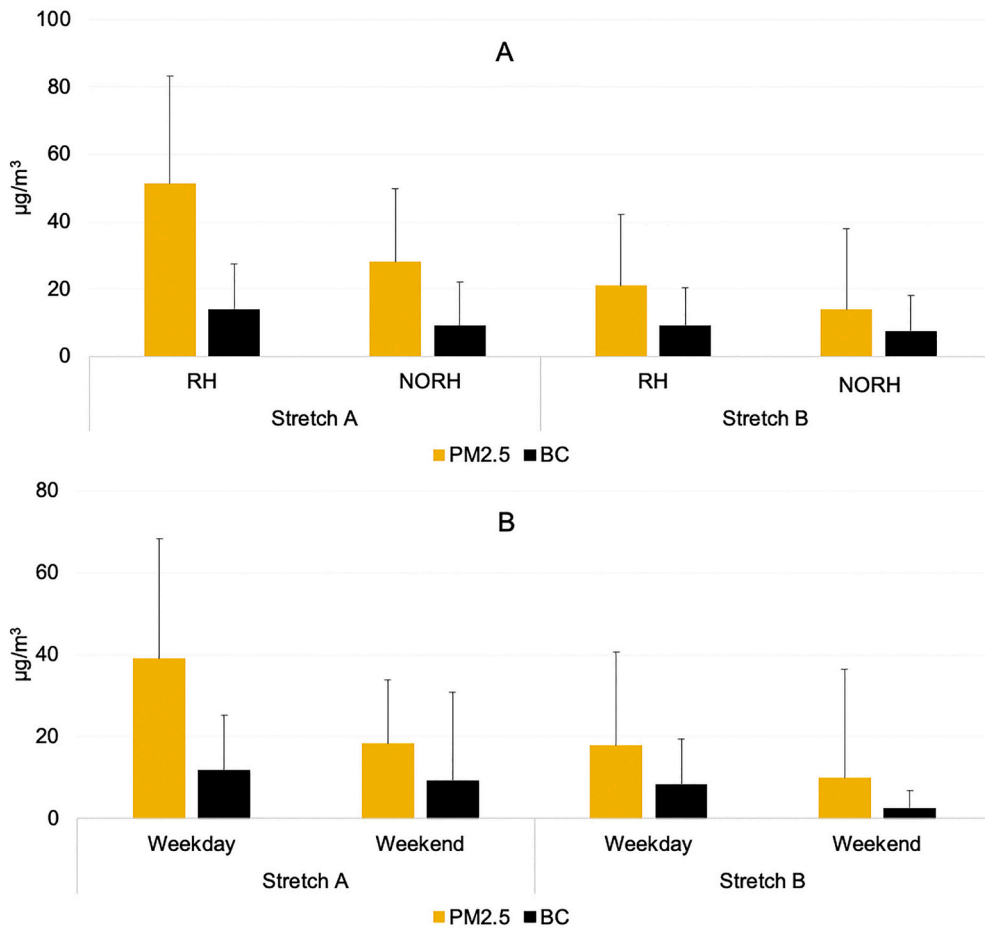


Fig. 3. Variation in $PM_{2.5}$ and BC concentrations for (A) rush hour (RH) vs non-rush hour (NORH), and (B) weekdays vs weekends for the two selected stretches of bicycle paths.

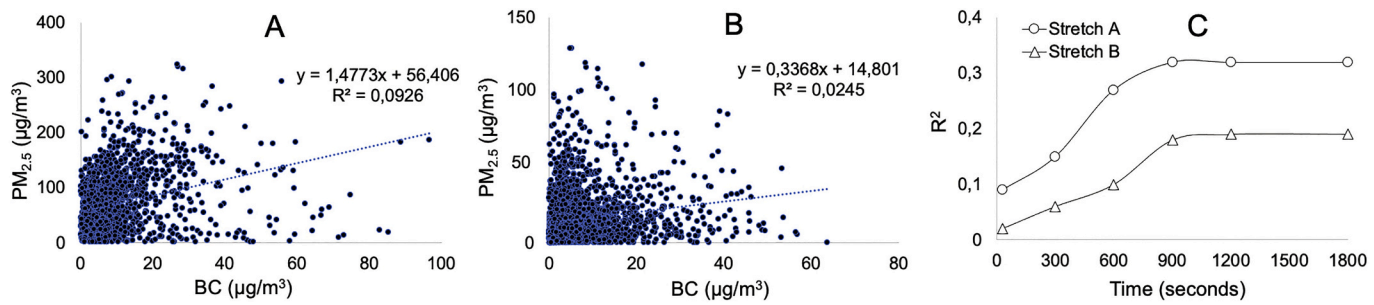


Fig. 4. Variations (R^2) between $\text{PM}_{2.5}$ and BC for (A) Stretch A and (B) Stretch B. Fig. (C) shows R^2 as a function of time.

buses and 250% more trucks transit through Stretch A compared with Stretch B (Table 1). Heavy-duty diesel vehicles (HDDV)—such as buses and trucks—are major contributors to $PM_{2.5}$ and BC emissions in urban contexts (Targino et al., 2016), accounting for <5% of the total vehicle fleet in Bogotá (SDM, 2019b). Increased emissions are largely influenced by the fleet's age, as the efficiency of combustion processes deteriorates with time.

Cyclist exposure to $PM_{2.5}$ along Stretch A was higher than values observed in European and American cities, including Helsinki ($24 \mu\text{g}/\text{m}^3$, Okokon et al., 2017), Rotterdam ($27 \mu\text{g}/\text{m}^3$, Okokon et al., 2017), Stockholm ($7.35 \mu\text{g}/\text{m}^3$, Merritt et al., 2019), and Minneapolis ($8.6\text{--}9.8 \mu\text{g}/\text{m}^3$, Hankey and Marshall, 2015). The $PM_{2.5}$ values along Stretch A were below ($68 \mu\text{g}/\text{m}^3$, Franco et al., 2016) and within the upper the exposure range observed along other bicycle paths in Bogotá ($19\text{--}77 \mu\text{g}/\text{m}^3$, Morales et al., 2017). In contrast, the concentrations along Stretch B were within the lower range. Along both routes, cyclist exposure to BC was higher than reported in Minneapolis ($0.7\text{--}2.3 \mu\text{g}/\text{m}^3$, Hankey and Marshall, 2015), Helsinki ($3.1 \mu\text{g}/\text{m}^3$, Okokon et al., 2017), Stockholm ($2.35 \mu\text{g}/\text{m}^3$, Merritt et al., 2019), and Antwerp ($2.47 \mu\text{g}/\text{m}^3$, Hofman et al., 2018), but were lower than the concentrations reported at other sites in Bogotá ($15.3 \mu\text{g}/\text{m}^3$, Franco et al., 2016; $10\text{--}42 \mu\text{g}/\text{m}^3$, Morales et al., 2017). However, to directly compare the cyclist exposure data of Bogotá with other cities across the world, the differences in vehicle technology, fuel quality, vehicle composition, and road characteristics (as well as other variables) must be considered.

3.2. Temporal variability during mobile monitoring

Pollutant concentrations were higher during RH relative to NORH on both routes (Fig. 3A). The difference in median $PM_{2.5}$ concentrations between the two periods was -52.6% for Stretch A and -50.0% for Stretch B (Table 2), which can be attributed to the reduction in the number of vehicles after RH, particularly motorcycles (25% Stretch A and 6% Stretch B), buses (19% Stretch A and 8%

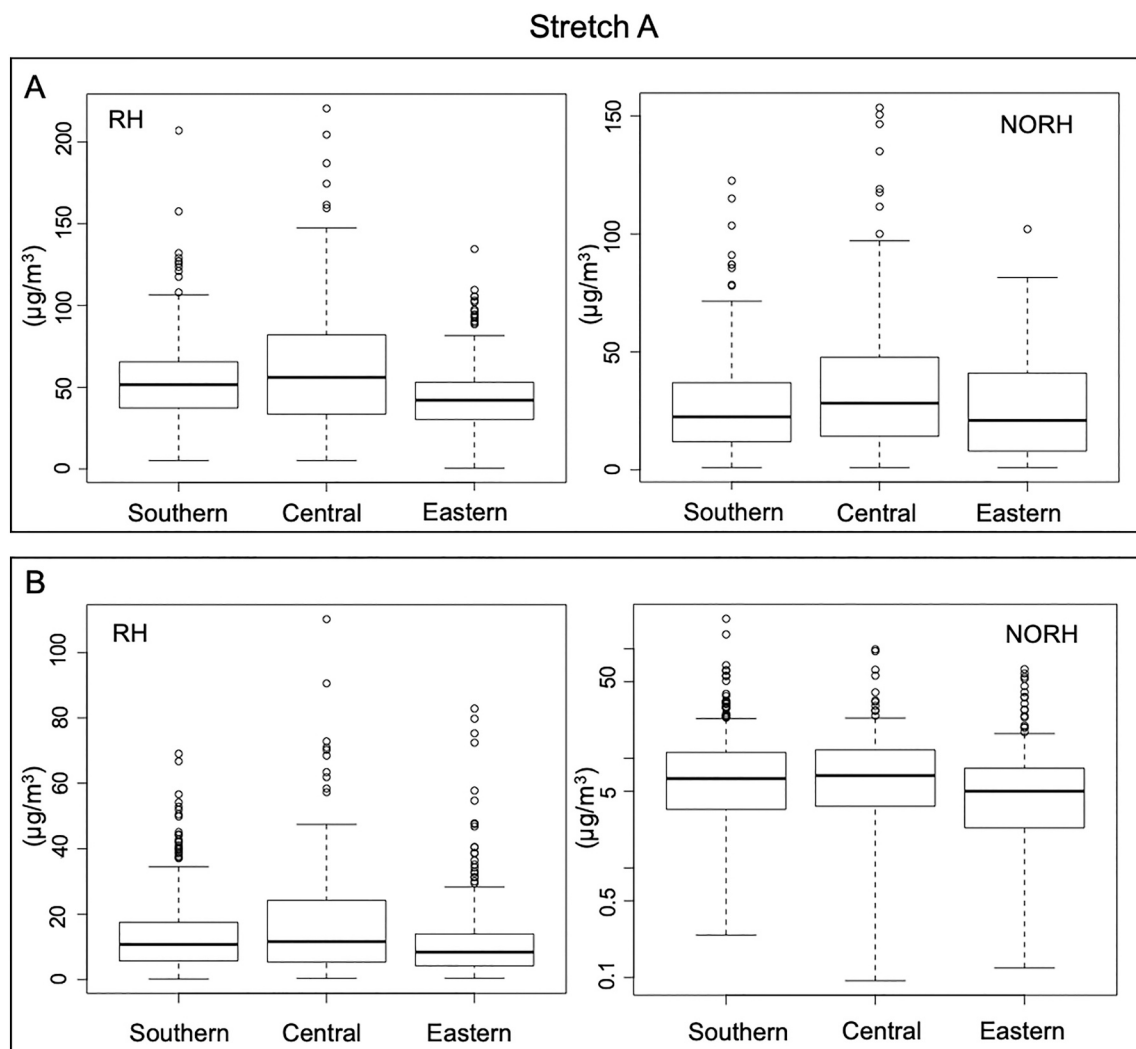


Fig. 5. Concentration of (A) $PM_{2.5}$ and (B) BC for three sections of Stretch A during rush hour (RH) and non-rush hour (NORH).

Stretch B), and trucks (21% Stretch A and 8% Stretch B). Cars were the only vehicle type that showed a higher average percentage during NORH (20% Stretch A and 5% Stretch B), which suggests that the number of gasoline light-duty vehicles (GLDV) does not seriously affect cyclist exposure to $PM_{2.5}$. Notably, the “pico y placa” measure (a restriction on private vehicles twice a day between 6:00 and 8:30 h and 15:00 and 19:30 h according to working hours) focuses on reducing GLDV vehicles but excludes more heavily polluting vehicles, such as HDDVs (Targino et al., 2016).

Our results suggest that cyclists using the two bicycle paths are exposed to higher concentrations of $PM_{2.5}$ during RH, despite the implementation of the “pico y placa” measure. As this trend was observed in two distant sectors in the city, we suggest that lower $PM_{2.5}$ concentrations likely occur across other bicycle paths in Bogotá during NORH; this finding highlights the relationship between cyclist exposure to $PM_{2.5}$ and the diurnal changes in vehicular traffic volume.

Compared to RH, the difference in BC concentrations during NORH was -40.2% and -32.3% for Stretches A and B, respectively (Table 2). This reduction is likely related to the less traffic during NORH. In particular the reduction in the number of buses, trucks and motorcycles (19%, 21% and 25% respectively for Stretch A and 8%, 8% and 6% respectively for Stretch B). Difference in the proportion of BC concentrations reduction for Stretch A and Stretch B can be associated to the less change in traffic flow between RH and NORH in Stretch B (Table 1).

The concentration of pollutants during the weekend was lower than that of weekdays (Fig. 3B). The median $PM_{2.5}$ concentrations reduced by 51.4% (Stretch A) and 43.1% (Stretch B), and BC concentrations decreased by 58.7% (Stretch A) and 74.7% (Stretch B). This highlights the notable impact of mobile sources on cyclist exposure. Interestingly, we observed similar BC concentrations during the weekend and the weekdays in Stretch A (Table 2). This confirms the continued activity of the fossil fuel combustion industries during weekends, which explains the observed background value of BC. In contrast, we observed a noticeable reduction in BC concentrations in Stretch B during the weekend (Fig. 3B), highlighting the improved air quality in response to the reduction of buses and trucks in this sector.

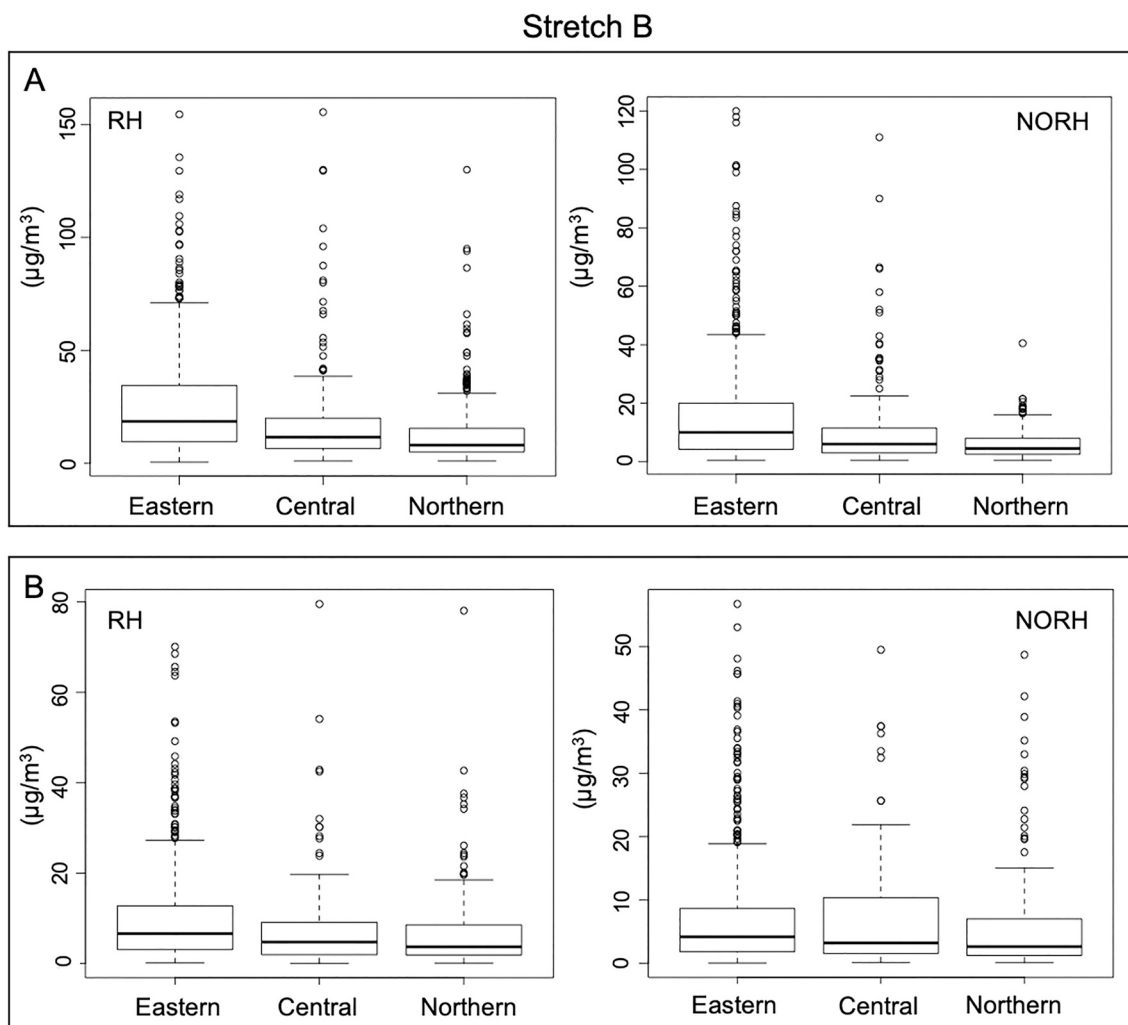
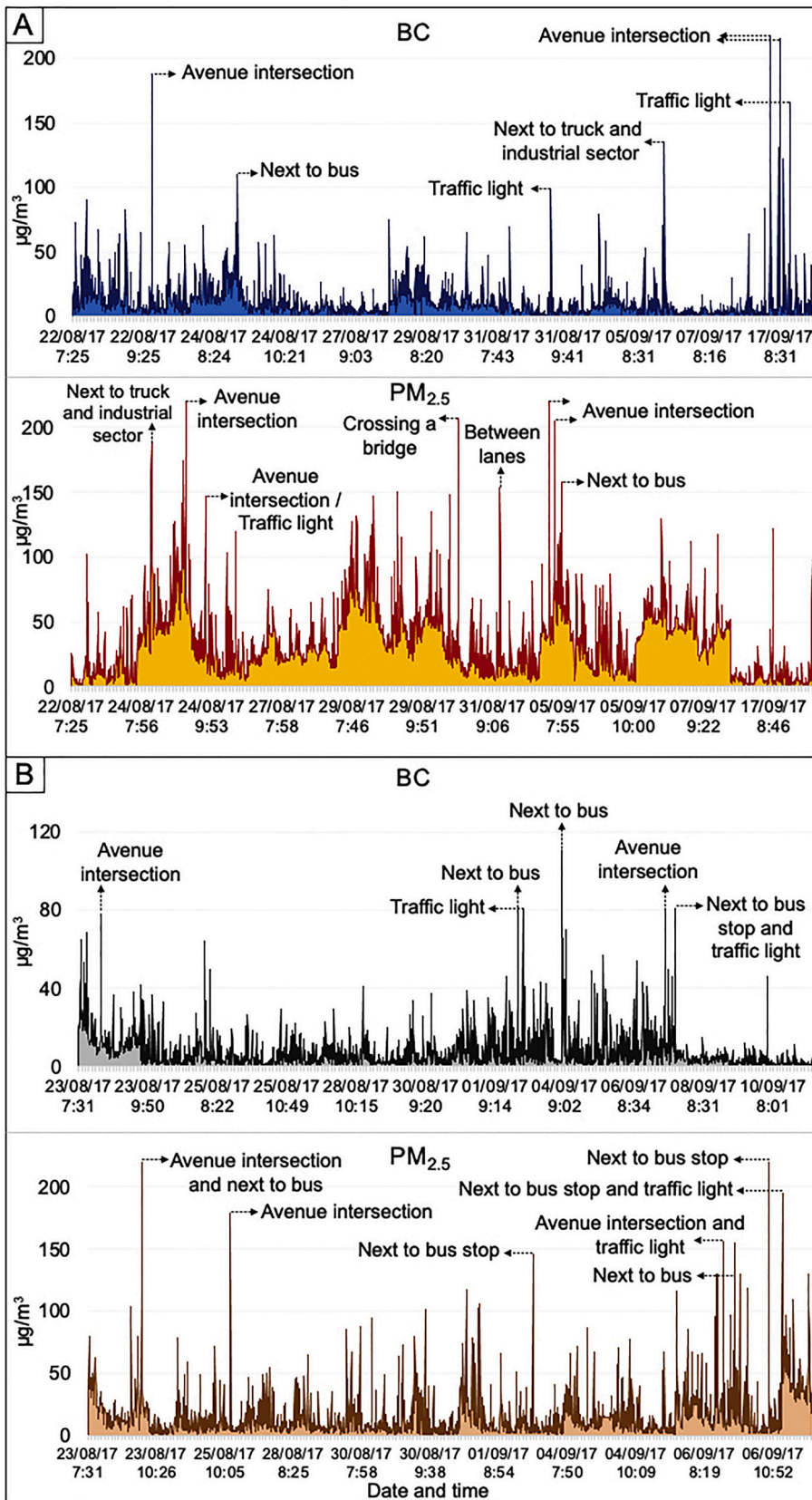


Fig. 6. Concentration of (A) $PM_{2.5}$ and (B) BC for three sections of Stretch B during rush hour (RH) and non-rush hour (NORH).



(caption on next page)

Fig. 7. Spatial and temporal distribution of PM_{2.5} and BC concentrations on (A) Stretch A and (B) Stretch B.

We calculated the variation between PM_{2.5} and BC using the coefficient of determination (R^2) for each of the two stretches. The total dataset was included, and the R^2 was calculated for the temporal measurement resolution ($t = 30$ s) and for time intervals of 300, 600, 900, 1200, and 1800 s (the sample size was reduced based on the time interval). The variation between PM_{2.5} and BC for the initial resolution sampling time (30 s) was modest ($R^2 = 0.09$ and 0.02 for Stretches A and B, respectively; Fig. 4A and B) and consistent with the results from previous cyclist exposure studies that used similar instruments and sampling periods (Hankey and Marshall, 2015). These low values may be related to meteorological factors (wind speed has been associated with differences in the average concentrations of measured pollutants; Jarjour et al., 2013), sampling time intervals (good correlations between these pollutants were not achieved at intervals of less than 1 min; Hankey and Marshall, 2015), and the proximity of bicycle users to vehicular exhaust pipes (a larger distance decreases the concentration of BC relative to PM_{2.5}; Yu et al., 2016). Instrumental limitations—such as DustTrak's inability to detect nanoparticles (the mass size distributions of BC from diesel engine tailpipes peak at 100–150 nm; Ning et al., 2013) and detection based on scattering (not suitable for detecting BC)—could also contribute to the weak association between PM_{2.5} and BC. Some studies have reported a better relation between these parameters in other transport modes, such as buses and cars (Okokon et al., 2017).

The variation between PM_{2.5} and BC generally increased with longer time intervals, ranging from $R^2 = 0.02$ – 0.09 ($t = 30$ s) to $R^2 = 0.19$ – 0.32 ($t = 1800$ s) (Fig. 4C). In both stretches where no considerable increase in the R^2 value was observed, the coefficient of determination increased for the time intervals of 300–900 s. Longer time intervals, therefore, strengthened the R^2 values at the expense of spatial and temporal resolution.

3.3. Spatial variability within each stretch

Figs. 5 and 6 show the median PM_{2.5} and BC concentrations at three sections in Stretches A and B (weekdays only). The statistical analysis of each section during RH and NORH was conducted through the Wilcoxon signed rank test because the distributions were non-parametric.

In Stretch A, the highest median PM_{2.5} concentrations were observed in the Central section (Carrera 50), ranging from $28.3 \mu\text{g}/\text{m}^3$ (IQR = 33.5) during NORH to $56.0 \mu\text{g}/\text{m}^3$ (IQR = 48.5) during RH. The difference between PM_{2.5} concentrations during RH and NORH for the Central section was statistically significant ($p = 0.000$). These concentrations were 33.3–34.5% higher than those observed in the Eastern section, which registered the lowest values (Fig. 5A). The Central section had a dedicated bicycle lane that was less than 1 m from the road. Lonati et al. (2017) reported that the absence of a physical barrier between the bicycle lane and road combined with high vehicular flows (both in RH and NORH) increases PM exposure.

The median BC concentrations showed variability in the three sections of Stretch A (Fig. 5B), ranging from 8.5 – $11.6 \mu\text{g}/\text{m}^3$ during RH and 5.0 – $7.0 \mu\text{g}/\text{m}^3$ during NORH. The highest RH and NORH values were observed in the Central and Southern sections, respectively; this can be linked to the vehicle fleet composition, with greater bus and truck numbers transiting these routes. The differences between PM_{2.5} concentrations during RH and NORH for these both sections were statistically significant ($p = 0.000$). The Southern section was open and had one of the longest distances between the bicycle path and traffic lanes (Table 1); however, this section (unlike the other two) had a high vehicle flow (2400–3400 vehicles/h) and was influenced by both bus (from the mass transit system; Transmilenio) and industrial emissions. Recent studies have shown that the background BC value predominantly determines the exposure of cyclists to pollutants (Hofman et al., 2018). The statistical analysis showed that the differences between the pollutants concentrations for RH and NORH were statistically significant for all sections (Supplementary data).

In Stretch B, the highest median PM_{2.5} concentrations were recorded in the Eastern section (Carrera 11), with values ranging from $10.0 \mu\text{g}/\text{m}^3$ (IQR = 16.0) during NORH to $18.5 \mu\text{g}/\text{m}^3$ (IQR = 25.0) during RH; these values are double the figures measured in the Northern section where the lowest values were recorded (Fig. 6A). The difference between PM_{2.5} concentrations during RH and NORH for the Northern section was statistically significant ($p = 0.000$). The bicycle path in the Northern section was situated along a wide tree-lined separator at a distance of 4–5 m from the traffic (Table 1), which reduced PM exposure (Peters et al., 2014; Pattinson et al., 2017). The design and location of the bicycle path played a predominant role in cyclist exposure to PM_{2.5}, as the Northern section had the lowest exposure to PM_{2.5}, despite having the highest number of cars in Stretch B (> 1000 vehicles/h).

The median BC concentrations showed little variability between the sections of Stretch B (Fig. 6B), remaining between 3.7 and $6.6 \mu\text{g}/\text{m}^3$. The Eastern section did not show a large difference in BC concentrations, despite having three- and six-times higher bus flows than that of the Central and Northern sections, respectively. In addition, the distance between the bicycle path and traffic was less than 4 m. This low exposure may be linked to the meteorological conditions and cycling direction, as cyclists travel in the opposite direction to that of the prevailing wind. Unfortunately, this assumption cannot be confirmed, as wind speed was not measured in the study. However, previous studies have demonstrated the dominant effect of wind on pollutant concentrations and cyclist exposure, regardless of traffic volume (Thai et al., 2008; Jarjour et al., 2013). BC concentrations above $20 \mu\text{g}/\text{m}^3$ were frequently measured in the Eastern section (Fig. 6B); this suggests that cyclists are exposed to high concentrations of pollutants and are at risk of both short- and long-term health impacts. These peaks are generally indicative of high traffic points (Jarjour et al., 2013) and intersections with traffic lights (Jayaratne et al., 2009), which is consistent with the characteristics of the Eastern section. The statistical analysis, of each section, showed that the differences between the concentrations of particulate matter for the RH and NORH conditions were statistically significant for all the sections. In contrast, the variations in BC concentrations for the RH and NORH conditions were only significant for the central section ($p = 0.000$). Meanwhile, the differences between BC concentrations during RH and NORH for the Central and

Northern sections were not statistically significant ($p = 0.465$ and $p = 0.117$, respectively) (Supplementary data).

Fig. 7 presents conditions associated with high $PM_{2.5}$ and BC exposure of cyclists. High pollutant concentrations are typically associated with specific events, such as stopping at traffic lights and street intersections, crossing bridges, and the presence of heavy vehicles. This information reflects the importance of avoiding these locations when selecting routes and designing cycling infrastructure.

3.4. $PM_{2.5}$ chemical analysis

The elemental chemical composition of the $PM_{2.5}$ samples collected from Stretch B is presented in Table 3. Ca, Fe, Al, and Mg showed the highest concentrations, with values ranging between 63 and 286 ng/m^3 . These elements are abundant in the Earth's crust (Rudnick and Gao, 2003) and are associated with mineral dust and dust resuspension.

The high concentration of Ca may indicate fugitive emissions from construction (Shen et al., 2016) or poor pavement conditions (Amato et al., 2014). Moreover, the significant correlation between these elements ($0.95 > r > 0.56$) suggests a common origin. The higher concentrations observed on Sundays may be associated with resuspension episodes linked to the higher speed of vehicles under low traffic.

The mean concentrations of selected trace elements occurred in the following order: $Cu > Zn > Ba > Mn > Pb > Sr > Cr > Sb > Sn > Ni > V > As > Cd > Co$. The most abundant elements were Cu, Zn, and Ba with concentrations of $>10 ng/m^3$ (Table 3); this coincides with the findings of a recent study conducted in Bogotá (Ramírez et al., 2020). These elements have been linked to vehicle emissions—including the mechanical wear of brakes and tires (Lin et al., 2015)—and vehicle exhaust emissions from fuel and lubricating oil combustion (Liu et al., 2018).

Ni, Pb, Cr, Sb, Co, Cd, Sr, Mn, and Sn have also been linked to traffic emissions (Lin et al., 2015; Jaiprakash, 2017; Ramírez et al., 2019). Zn is particularly abundant in the $PM_{2.5}$ fraction of diesel vehicles (Fushimi et al., 2016); Mn is used to improve detonation and is therefore characteristic of gasoline vehicle exhaust emissions (Cheung et al., 2010). Cr and Sb showed the highest concentrations on weekdays (41% and 7%, respectively) and are typical tracers of brake and tire wear (Pant and Harrison, 2013). The high concentrations are likely linked to the high traffic flow on weekdays (> 4000 vehicles/h, Table 1) and the low vehicular speed reported on Carrera 11—one of the slowest road corridors in the city (mean speeds of 11 km/h) (SDM, 2018).

The presence of Ni, V, and As is indicative of oil combustion emissions (Hao et al., 2018). The significant correlation between these elements—particularly between V and As ($r = 0.66$)—indicates a similar source. A V/Ni ratio of <2 is indicative of gasoline and diesel combustion, while values >2 are indicative of heavy fuel combustion (Lin et al., 2015). We observed a V/Ni ratio of 0.41 in this study, inferring high contributions from vehicular combustion. However, charcoal burning has also been linked to emissions of Cr, Co, Ni, Cu, As, Cd, Pb, and Zn (Kabir et al., 2011) and commonly occurs in restaurants within this sector. Although we detected low concentrations of some metals, such as Cr, Ni, As, Co, Sb, Pb, and Cd, these elements are highly carcinogenic and can adversely impact human health via inhalation (Jaishankar et al., 2014).

3.5. Inhalation rate

We measured HR, oxygen saturation (SpO_2), and respiratory rate (RR) to evaluate the VR. The mean of each parameter showed low variability (Table 4).

The median VR ranged between 11.31 and 12.63 L/min on Stretch B (Fig. 8). We observed no increase in physical demand

Table 3
Chemical composition of ambient $PM_{2.5}$ (ng/m^3).

| Element | Weekday (mean) | SD | Weekend (mean) | SD | Whole period (mean) | SD |
|---------|----------------|------|----------------|------|---------------------|------|
| Ca | 272 | 175 | 327 | 182 | 286 | 165 |
| Fe | 110 | 42.3 | 166 | 122 | 124 | 64.0 |
| Al | 91.7 | 42.2 | 203 | 155 | 119 | 85.8 |
| Mg | 55.6 | 35.5 | 86.7 | 4.2 | 63.4 | 33.3 |
| Cu | 15.1 | 6.61 | 32.4 | 12.6 | 19.4 | 10.9 |
| Zn | 12.2 | 7.24 | 15.3 | 7.15 | 13.0 | 6.84 |
| Ba | 10.1 | 4.51 | 12.9 | 2.87 | 10.8 | 4.15 |
| Mn | 1.90 | 1.13 | 1.90 | 1.77 | 1.90 | 1.17 |
| Pb | 1.48 | 1.58 | 1.91 | 0.71 | 1.58 | 1.38 |
| Sr | 1.37 | 1.02 | 1.36 | 0.52 | 1.37 | 0.88 |
| Cr | 1.11 | 1.20 | 0.65 | 0.38 | 0.99 | 1.04 |
| Sb | 0.87 | 0.91 | 0.81 | 0.40 | 0.85 | 0.78 |
| Sn | 0.67 | 0.84 | 0.81 | 0.68 | 0.70 | 0.75 |
| Ni | 0.50 | 0.51 | 0.47 | 0.08 | 0.49 | 0.43 |
| V | 0.17 | 0.08 | 0.29 | 0.27 | 0.20 | 0.14 |
| As | 0.11 | 0.12 | 0.14 | 0.06 | 0.12 | 0.11 |
| Cd | 0.05 | 0.06 | 0.05 | 0.04 | 0.05 | 0.06 |
| Co | 0.03 | 0.02 | 0.03 | 0.04 | 0.03 | 0.02 |

SD: standard deviation.

Table 4
Variables of cyclists linked to field measurements.

| | Mean | SD |
|----------------------|-------|------|
| VR (L/min) | 11.03 | 3.36 |
| SpO ₂ (%) | 91.00 | 2.37 |
| RR (breaths/min) | 18.16 | 1.76 |
| HR (beats/min) | 84.66 | 11.7 |

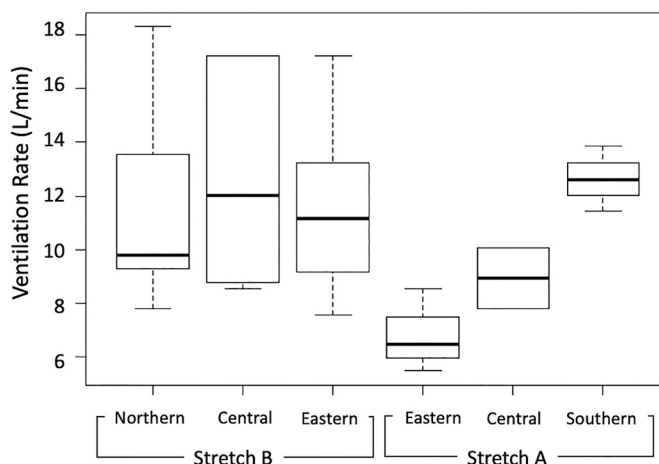


Fig. 8. Ventilation rate for each section on Stretches B and A.

throughout each journey; therefore, we identified no increase in both oxygen demand and inhaled air volume. The previous situation was favorable for this experiment as it resulted in a fairly stable relationship with exposure, which minimize possible confusion for individual variables. However, the actual scenario for road cyclists is different as their speed and intensity are highly variable throughout their journey; their physiological variables are therefore likely influenced by urban (e.g., inclined terrain) and social factors (e.g., distance from the workplace).

We observed different inhalation characteristics for Stretch A, which showed notable variability (Fig. 8). Median VRs of 6.84 L/min, 8.94 L/min, and 12.63 L/min were observed for the Eastern, Central, and Southern sections, respectively. The doubling of VR from the Eastern to the Southern section may be due to the presence of bridges and changes in topography, which altered the slope and increased the physical activity of cyclists. Studies have shown that the VR of cyclists is 4.3 times higher than that of car passengers, which increases their exposure to air pollutants (Int Panis et al., 2010). This finding highlights the need to focus on controlling potential variables that increase cyclist exposure to pollutants. The VR remained fairly stable in Stretch B and showed similar values to the Southern sector of Stretch A, which can be explained by the fact that these sections tend to be uphill.

The Central section on Stretch A (with similar distances from each section) has a shorter travel time (7.5 min) and higher concentrations of PM_{2.5}; this limited the inhalation rate of pollutants, reducing cyclist exposure. This was evident in the estimates of PM_{2.5} inhalation rates (Fig. 9), where values in the Central section reached the same concentration as that of the Eastern section, despite having a lower vehicle density. In contrast, the Southern section showed the highest cyclist exposure to pollutants. We, therefore, advised that cyclists use the bicycle path located at a further distance from the road to minimize exposure concentrations. The high volume of buses and trucks in this corridor is the main cause for high pollutant concentrations, despite the road being relatively open. Therefore, although we registered similar PM_{2.5} concentrations in all sections, with slightly higher concentrations in the Central section, the Southern section showed the least favorable conditions for cyclists.

Stretch B had a high volume of cyclists throughout the day in the Eastern section—an area with higher concentrations of PM_{2.5}—which was directly reflected in the concentrations of PM inhalation (Fig. 9). This circumstance is a serious disadvantage to cyclists; however, PM_{2.5} concentrations in the Eastern section were only 1.3 and 1.6 times higher than that of the Central and Southern sections, respectively. These differences are equivalent to PM_{2.5} inhalation rates of 4.3–4.4 µg.

This is an estimation of the inhalation rates since we didn't conduct any tests to produce a standardized ventilation rate curve. Hence, we instead used the Do Vale equation (Do Vale et al., 2015). However, this assumption can lead to errors in the determination of exposure because the prediction uses variables, such as gender, age, and altitude above sea level. The PM_{2.5} inhalation results establish the specific exposure load in cyclists who use a mode of transport that does not generate emissions; however, according to other investigations, cyclists are constantly exposed to atmospheric pollutants (Int Panis et al., 2010). This study highlights the potential risks of developing a wide range of adverse health effects, including respiratory diseases and strokes (Villeneuve et al., 2006), adverse birth outcomes (Arroyo et al., 2016), cognitive effects, and dementia (Baumgart et al., 2015; Chen et al., 2017). Future research should focus on monitoring the health effects of different population groups of cyclists and those related to other modes of transport by

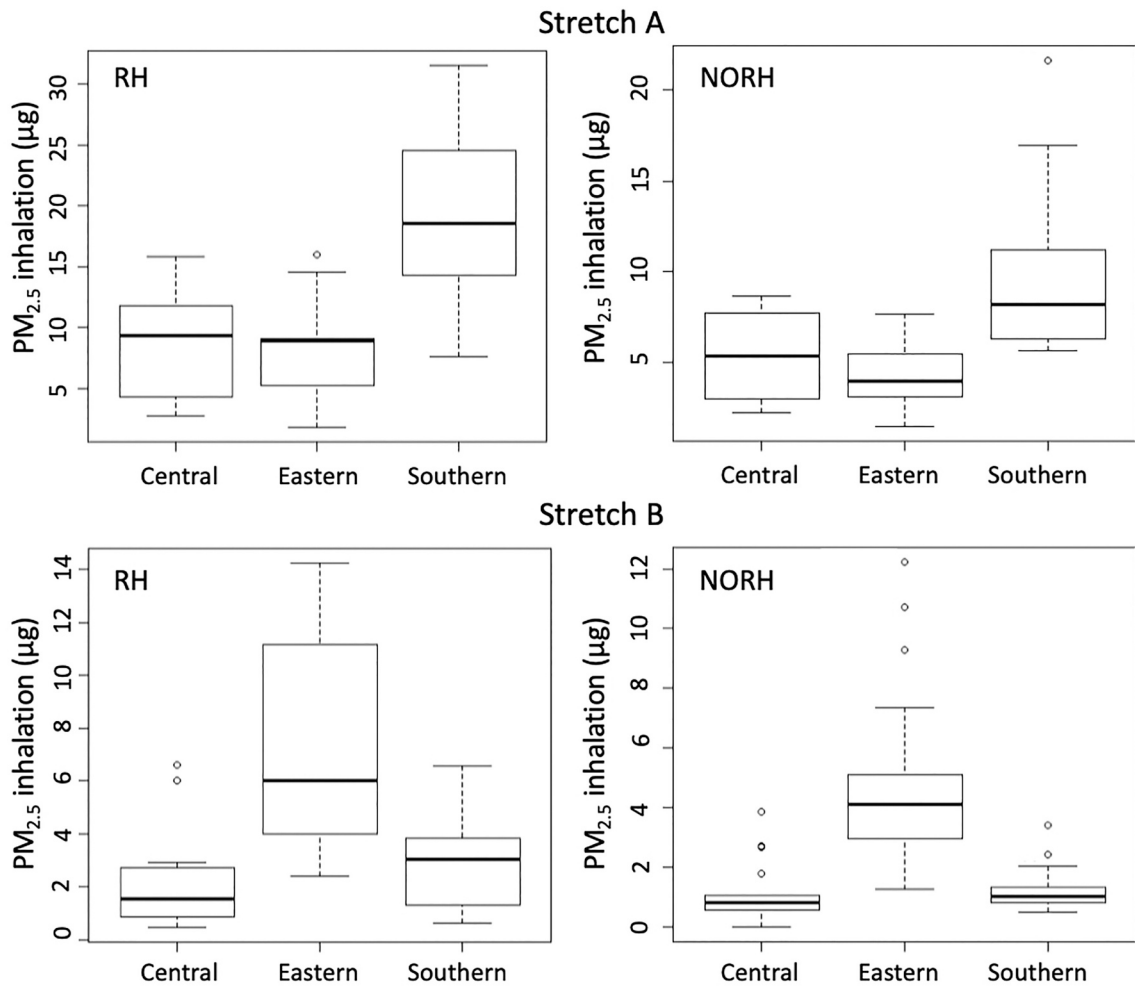


Fig. 9. Inhalation of PM_{2.5} for the three sections of Stretches A and B during rush hour (RH) and non-rush hour (NORH).

considering environmental measures, social practices, and individual conditions. It is also important to establish (and to include in the analysis) a background baseline of PM_{2.5} and BC concentrations to better understand the impact of traffic on actual PM exposure levels.

4. Conclusions

This study assessed the exposure and potential health impacts of cyclists to PM_{2.5} pollution along dedicated bicycle lanes in Bogotá. We found that the cyclists were exposed to high PM_{2.5} concentrations, indicating a risk to human health. Cyclist exposure to PM_{2.5} and BC at the studied bicycle lanes was closely linked to vehicular traffic. Higher exposure was observed in bicycle lanes without physical barriers between the bicycle path and the road. We detected various metals in the PM_{2.5} samples—such as Cr, Ni, As, and Cd—which have serious health implications due to their carcinogenic effects. The chemical results of the PM_{2.5} samples confirm the enhanced risk of mobile sources on the health of cyclists using the studied bicycle paths. Our results contribute to the better understanding of traffic-related pollution problems in Bogotá and highlight the need to consider air quality when designing and implementing cycling infrastructure in Latin American cities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2020.100767>.

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