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Research article

A first screening of black carbon concentrations whilst commuting by diesel-fuelled buses in Montevideo, Uruguay

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ABSTRACT

Urban bus commuters are exposed to a range of traffic-related air pollutants, including black carbon (BC) particles, a major hazardous component of vehicle exhaust emissions. This study provides the first assessment of in-cabin BC concentrations aboard diesel-fuelled public buses in Montevideo, Uruguay. Our objective was to assess BC concentrations during evening peak commuting hours and to examine how specific traffic elements, such as bus stops, traffic lights and traffic volume, influence exposure levels. We implemented a structured sampling strategy to maximise the reliability of our findings by collecting data during four consecutive weekdays within the same timeframe (17:00–18:00 h) in May 2019. We measured BC concentrations at a high-frequency sampling rate using a handheld aethalometer, focusing on two bus routes. The mean in-cabin BC concentration was 14.28 ± 14.38 μg m^{-3}, with considerable spatial variability. Notably, BC concentrations were significantly higher at traffic lights and bus stops, where stop-and-go driving patterns and idling contribute to increased emissions, while the constant opening and closing of doors allows outside air to infiltrate. We found a positive trend between traffic volume and median BC concentrations, consistent with previous studies conducted in other cities. Compared to similar studies in South America, BC concentrations were found to be intermediate, but considerably higher than those observed in North American and European cities. This study underscores the importance of implementing targeted interventions in urban transport policies, specifically addressing congestion points, like bus stops and traffic lights, to effectively reduce commuter exposure to harmful air pollutants. Whilst our study focused on Montevideo, interventions to combat traffic-related air pollutants should be expanded across Latin American cities, where reliance on diesel-powered public transportation remains prevalent.

1. Introduction

Latin America is one of the most urbanised regions in the world, with approximately 80% of the population living in urban areas [1]. In urban environments, public transportation plays an indispensable role in the population's daily lives. It allows moving a substantially larger number of people than private modes, facilitating commuting to work and enabling access to a wider range of opportunities across different parts of the city [2]. Public transport modes also reduce traffic congestion and creates a more sustainable transportation system. This is particularly evident for mass systems, such as Bus Rapid Transit (BRT), train and subways, which have

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large capital productivity (defined as the ratio of passenger boardings per day to number of buses or trains) [3]. Furthermore, public transportation enhances sustainability by reducing greenhouse gas and criteria air pollutant emissions, thereby decreasing the ratio of pollutant emitted per passenger-kilometre travelled [4]. Buses, particularly, are attractive options not only because of the affordability but also adaptability, as they require minimal modifications to existing road infrastructure for their installation, as is the case of BRT systems [5].

In Latin America, reliance on public urban transport is highly variable, but remains a significant mode share, ranging from 28% in Curitiba, Brazil to 75% in La Paz, Bolivia [6]. The region stands out for its dominant reliance on public urban buses, boasting the world's highest per capita bus ridership [7,8]. However, public bus fleets in the Global South predominantly rely on fossil fuels and usually lack essential after-treatment technologies, such as diesel particulate filters. Diesel buses are a particular concern, as they emit significantly higher levels of particulate matter, hydrocarbons, and carbon monoxide compared to biodiesel alternatives [9]. These pollutants can infiltrate passenger cabins, posing potential health risks to commuters [10–12]. Consequently, the well-documented advantages of public transportation, such as congestion reduction in central urban areas and affordability, may be offset by the negative health impacts associated with exposure to elevated in-cabin air pollutant concentrations aboard aging and outdated buses.

Although urban residents spend on average only between 6 and 10% of their day in transport microenvironments [13–15], this brief exposure yields disproportionately high dose. Exposure to air pollution has been associated with health risks to commuters, including respiratory problems and cardiovascular diseases [16–18]. Black carbon (BC) is a particulate byproduct of incomplete combustion and a major component of traffic-related air pollution. In 2012, the World Health Organization classified diesel emissions as carcinogenic, and its European branch suggested creating a public health standard for BC. Due to its small size (often less than 2.5 μm in diameter), BC can penetrate deeply into the lungs and even enter the bloodstream, posing a significant health risk and contributing to premature mortality [19,20]. Studies have linked BC exposure to decrease in lung function and airway inflammation [21] and cardiorespiratory related mortality [22].

Lim et al. [23] and Targino et al. [11] demonstrated that commuters using diesel-fuelled buses in both New Zealand and Brazil experienced increased exposure to fine particulates (including BC) at intersections, bus stops and traffic lights. Stop-and-go driving patterns at these congestion hotspots lead to higher exhaust emissions [24]. Additionally, when buses stop or idle, pollution-laden plumes from both nearby idling vehicles and self-pollution from the bus's tailpipe can infiltrate the bus cabin [25,26].

In recent years, there has been a growing body of research investigating in-cabin air pollutant concentrations on bus systems in Latin American cities, such as Bogotá [27], Curitiba [10] and Mexico City [28]. However, the number of such studies remains significantly lower or outdated (*e.g.*, Refs. [29,30]) as compared to developed nations. This raises questions regarding the representativeness of current studies, since they may not encompass the diverse mobility patterns and variations in bus infrastructure found across Latin America.

To address this regional scientific gap, we present the first exposure study of its kind conducted on public buses in Montevideo, Uruguay. This research broadens the geographic scope of existing literature and aims to achieve a more comprehensive understanding of in-cabin air quality challenges across Latin America. Our study explores the interplay between bus route characteristics, traffic volume, and in-cabin BC concentrations, with the goal of providing data for effective mitigation strategies.

2. Methods

2.1. Study area

Montevideo, the capital city of Uruguay, is home to 1.32 million inhabitants and is situated at geographic coordinates 34°52′ S, 56°10′ W, at an elevation of 43 m above sea level. The city exhibits a humid subtropical climate (Cfa), characterised by a mean annual air temperature of 16.8 °C and mean annual precipitation of 1163.1 mm, distributed relatively evenly throughout the year (1991–2020 climatological normals). On average, the city experiences 85 days of rainfall each year exceeding 1 mm [66].

Montevideo's public transportation is predominantly based on buses, while taxis and shared modes of transport, such as bicycles, are used much less frequently [31]. The bus network is run by four companies and consists of 145 lines, with 1528 buses serving 4718 stops and three major transfer stations [32]. The vehicle fleet (as of 2018, which closely aligns with the 2019 study period) is dominated by automobiles (43.2%), followed by motorcycles (35.2%) and vans (15.8%), while buses account for only 0.8% of the fleet [67].

The study was conducted during selected evenings in May 2019, a period preceding the typically colder winter months when atmospheric particulate matter concentrations (specifically, fine particles, $PM_{2.5}$) are the largest [33]. This timeframe was selected to minimise the influence of residential wood combustion, a prevalent heating source during colder months, allowing for a primary focus on traffic-related emissions.

2.2. Data collection

BC data were collected using a handheld aethalometer (model AE51, Aethlabs, USA) whilst commuting on two different bus lines. The AE51 operates on the principle of particle accumulation and the absorption of radiation. Particles are drawn into the instrument via the sampling line at a flow rate of 150 mL min^{-1} and collected on a Teflon filter installed in the detection chamber. A radiation beam (λ = 880 nm) strikes the exposed part of the filter and the instrument then measures the change in attenuation every 10 s to determine how much of this radiation is absorbed by the particles. To calculate the BC mass on the filter, a built-up algorithm relates the attenuation and the wavelength-dependent cross-sectional absorption coefficient provided by the manufacturer via a linear relationship. A detailed description of the working principle of the AE51 can be found elsewhere (*e.g.*, Ref. [34]). The measurements were geo-referenced with data from a GPS datalogger (DG-100, GlobalSat, Taiwan).

Although air pollutant concentrations in urban environments usually peak during morning and evening rush hours, the campaign focused on evening conditions only due to limited manpower and financial resources. We implemented a structured sampling strategy to maximise the reliability of our findings by collecting BC data once a day, between May 13–16, 2019, within the same timeframe (17:00–18:00 h) to minimise variations in traffic patterns. BC concentrations were measured by the study authors operating the instrumental pack as passengers on two bus lines. The researchers boarded bus 64 on Italia Ave. (marked as "Start" in Fig. 1) around 17:00 h each day, travelling westbound to Independencia Sq. in the city centre. There, they disembarked and transferred to bus 60, heading eastbound. The entire journey took approximately 85 min to complete.

The seat choice was based on availability, but usually in the middle of the buses, which ran without controlled ventilation settings and with windows opened according to the passengers' discretion. However, most windows were open during the trips. The buses had three double-folding doors for boarding and alighting passengers, with the tailpipe located at the lower left at the rear. Smoking is not permitted on board public buses in Uruguay. We used a logbook to record mobile operations, the opening and closing of doors, stops and other relevant occurrences which can influence the data.

Hourly weather data were sourced from Carrasco International Airport, situated approximately 13 km northeast of the start of the route and 22 km northeast of Independencia Sq.

2.3. Spatial analysis of in-cabin BC concentrations

The data from the GPS and AE51 were scanned and combined into georeferenced matrices based on coinciding times and days. For the spatial distribution of BC concentrations along the bus route, we aggregated the original data into 100-m street segments, following the methodology by Refs. [10,34]. All BC data falling within each segment were used to calculate descriptive statistics (mean, median, interquartile range, etc.) which were allocated to that segment. Aggregating the data along the route is a commonly used method in ground-based mobile measurement studies [35,36], as this approach lessens the impact of outliers resulting from incidental events. The analysis was conducted using QGIS 3.28.4.

2.4. Traffic data

Traffic data were compiled from radar and manual counts collected along the route and obtained from the Montevideo City Council, accessible through the Government of Uruguay's open data catalogue (https://catalogodatos.gub.uy). We used data that most closely matched the sampling month and year (May 2019). Manual traffic counts were conducted on 18 de Julio Ave. (points 1−11 in Fig. 1) in August 2017 and on Rivera Ave. (points 14−16 in Fig. 1) in June 2018. Total traffic volumes are presented as vehicles per hour (veh. h^{-1}) obtained within the 18:00 h timeframe, corresponding to the sampling period. Radar data for Acevedo Diaz St. (point 12) and Italia Ave. (point 13) were sourced from November 2018 and May 2019, respectively. Five-min radar data were aggregated into hourly totals for analysis, with mean traffic volumes, expressed as veh. h^{-1}, calculated between 16:00 and 18:00 h.

Georeferenced bus stops and traffic lights along the route were obtained from the Government of Uruguay's open data catalogue.

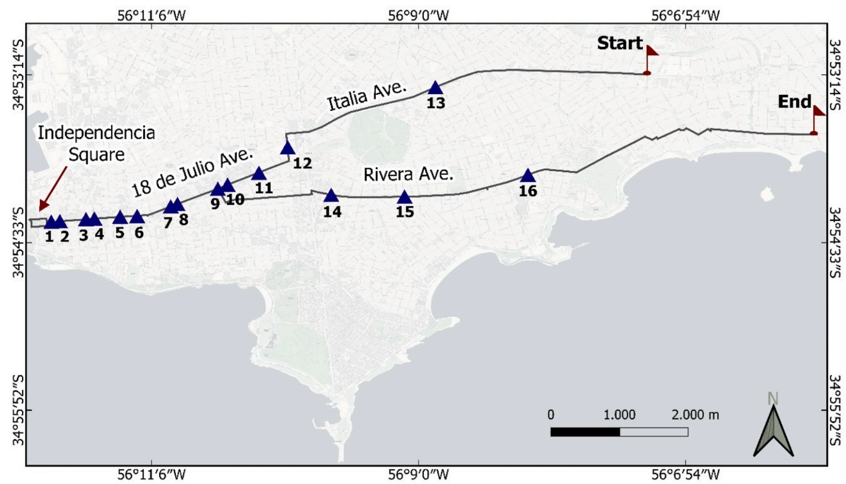

Fig. 1. Study area in Montevideo and bus route where in-cabin BC concentrations were collected. Numbered points mark the locations of traffic counts, which will be referred to throughout the text for analysis and discussion.

2.5. Relationships between traffic attributes and BC concentrations

To assess the influence of vehicular traffic and road attributes on in-cabin BC concentrations, we integrated BC measurements with georeferenced data on bus stops, traffic lights, and traffic volume along the route. First, we created 20-m radius non-overlapping buffers around each of these traffic attributes. Subsequently, we intersected the raw BC data collected on the four days with these buffers. All BC data point falling within an individual buffer were aggregated to calculate BC statistics (mean, median, percentiles, etc.). Whilst urban air pollution is influenced by environmental variables and the built environment, studies have demonstrated the significant role of exhaust emissions and traffic elements in determining traffic-related air pollutants (*e.g.*, Ref. [37]). This spatial analysis approach has been extensively used in urban air pollution research to delineate influence zones and to establish relationships between emission sources, traffic configurations and air pollutant concentrations [10,34,38].

3. Results

3.1. General overview

The study period was dry, with no recorded precipitation. Mean atmospheric conditions during the hours surrounding the sampling period (16:00–18:00 h) were: air temperature 17.1 °C (range 13–21 °C), relative humidity 65% (range 55–77%), and wind speed 4.2 m s^{-1} (range 2.1–6.2 m s^{-1}). The wind direction shifted from South on the first day to East-Northeast on the last day of the sampling period.

The mean in-cabin BC concentration during the experiment was 14.28 ± 14.38 μg m^{-3}, exhibiting substantial variability. This high standard deviation has been observed in other studies (*e.g*, Refs. [39,40]) and has been attributed to a combination of factors, including varying traffic density, traffic infrastructure and the characteristics of the surrounding built environment.

Direct comparisons of in-cabin BC concentrations across different studies are challenging due to the significant influence of vehicle-specific characteristics (*e.g.*, age, emission standards) and ventilation conditions (*e.g.*, windows open or closed). Additionally, external factors related to the built and natural environments, including road attributes (*e.g.*, street configuration, building height), city size, climate, and season, further complicate direct comparisons. These factors collectively hinder robust cross-study comparisons. However, to provide a broader international context for our study, we find it valuable to compare our data with other research (Fig. 2). Due to limited availability of studies in South America, we also incorporated results from global cities that employed the same BC measurement technique and wavelength as our study to ensure comparability.

Fig. 2 illustrates regional disparities in in-cabin BC concentrations, with the highest concentrations found in South American and South Asian cities, while North American and Australian cities demonstrate substantially lower values. Mean in-cabin BC concentrations in our study were intermediate compared to other South American (5.8−35.9 μg m^{-3}) and South Asian cities (10.8−21.0 μg m^{-3}), but exceeded those reported in Asian (8.7−11.6 μg m^{-3}), European (2.7−7.6 μg m^{-3}) and North American cities (1.7−3.1 μg m^{-3}) cities, as well as the single Australian study (2.3 μg m^{-3}). The values shown in Fig. 2 were extracted from studies conducted in cities listed in Table 1.

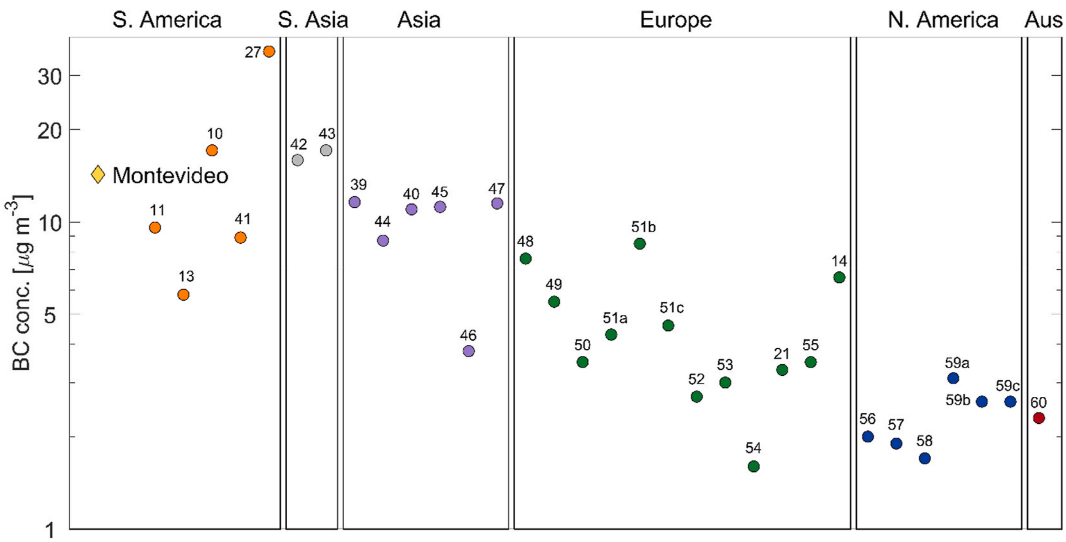

Fig. 2. Mean in-cabin BC bus concentrations in global cities, grouped by region. The numbers above each circle correspond to the studies and cities listed in Table 1.

Table 1
Compilation of mean in-cabin BC concentrations from peer-reviewed studies across multiple global cities. BC concentrations in parentheses indicate the reported ranges.

Mean BC (μg m^{-3})	City, country	Region	Source	Study number to interpret Fig. 2
14.28	Montevideo, Uruguay	South America	This study	
9.6	Londrina, Brazil		Targino et al. [11]	11
5.8	Londrina, Brazil		Carvalho et al. [13]	13
17.1	Curitiba, Brazil		Targino et al. [10]	10
8.9	São Paulo, Brazil		Contreras [41]	41
35.9	Bogotá, Colombia		Guzman et al. [27]	27
(10.8–21.0) 15.9	Karachi, Pakistan	South Asia	Javed et al. [42]	42
17.1	New Delhi, India		Pant et al. [43]	43
11.6	Hong Kong	Asia	Yang et al. [39]	39
8.7	Shanghai, China		Li et al. [44]	44
11.0	Hanoi, Vietnam		Quang et al. [40]	40
11.2	Istanbul, Turkey		Onat et al. [45]	45
3.8	Seoul, South Korea		Jeong and Park [46]	46
11.5	Singapore		Tran et al. [47]	47
7.6	Barcelona, Spain	Europe	de Nazelle et al. [48]	48
5.5	Barcelona, Spain		Moreno et al. [49]	49
(2.9–4.1) 3.5	Stuttgart, Germany		Bauer et al. [50]	50
4.3	Rotterdam, The Netherlands		Okokon et al. [51]	51a
8.5	Thessaloniki, Greece			52a
4.6	Helsinki, Finland			53a
2.7	Stockholm, Sweden		Merritt et al. [52]	52
3.0	Lisbon, Portugal		Martins et al. [53]	53
1.6	Lisbon, Portugal		Correia et al. [54]	54
3.3	Paris, France		Paunescu et al. [21]	21
3.5	Birmingham, UK		Delgado-Saborit [55]	55
6.6	Antwerpen, Belgium		Dons et al. [14]	14
2.0	Sacramento, USA	North America	Ham et al. [56]	56
1.9	New York, USA		Lovinsky-Desir et al. [57]	57
(0.4–2.9) 1.7	Beeville, USA		Zhang and Zhu [58]	58
3.1	Toronto, Canada		Van Ryswyk et al. [59]	59a
2.6	Ottawa, Canada			59b
2.6	Vancouver, Canada			59c
2.3	Brisbane, Australia	Australia	Williams and Knibbs [60]	60

3.2. BC spatial distribution

When data are skewed, contain outliers, or exhibit a large standard deviation, as seen in our dataset, the mean may not accurately represent the central tendency [34,61]. Therefore, we chose to use the median as a measure of central tendency for the BC spatial distribution. Fig. 3 shows that the median in-cabin BC concentrations along the route have substantial heterogeneity, with values

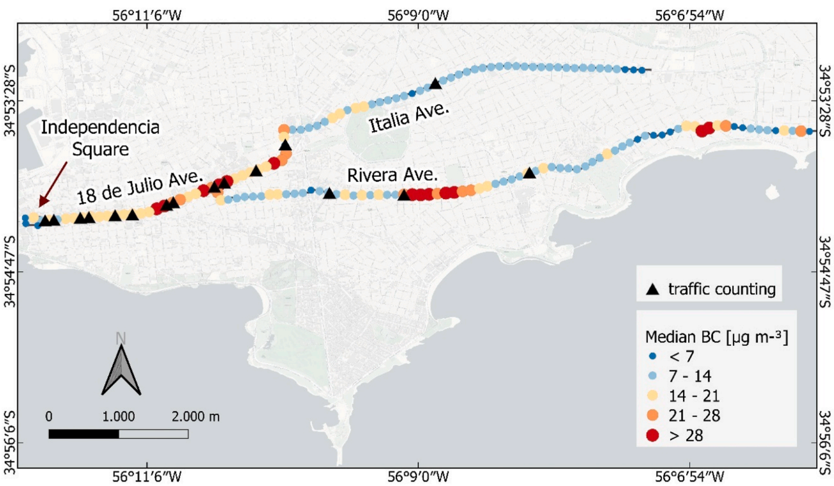

Fig. 3. Aggregated median in-cabin BC concentrations at 100-m resolution along a bus commute route. The colours indicate concentration ranges explained in the inset.

ranging from less than 7 to over 28 μg m^{-3}. Hotspots with BC concentrations exceeding 28 μg m^{-3} were identified along 18 Julio Ave. and more notably on extended segments of Rivera Ave. The locations with the highest traffic volumes yielded the highest BC concentrations, while those with the lowest traffic volumes showed substantially lower BC concentrations. For example, traffic count points 8 and 9 on 18 de Julio Ave. recorded mean rates of 1941 and 2209 veh. h^{-1}, respectively, and median BC concentrations of 27.28 and 38.84 μg m^{-3}. This is a four-lane road that features buildings flanking both sides of the road in a street-canyon configuration for most of its 3.30 km length. Street canyons are known for restricting air circulation and trapping air pollutants compared to more open street designs [62,63]. A 900-m hotspot on Rivera Ave. —a two-lane road that stretches eastward from the city centre, traversing residential neighbourhoods— reached a median BC concentration of 42.96 μg m^{-3}. This hotspot aligns with one of the highest traffic rates in the study area (mean of 1880 veh. h^{-1} at point 15). With few alternative parallel routes available, Rivera Ave. plays a key role as a primary thoroughfare connecting the city centre to the eastern neighbourhoods, with traffic volume comparable to or even larger than on 18 de Julio Ave.

Despite having a high traffic rate (mean of 1667 veh. h^{-1} at point 13), Italia Ave. exhibited lower BC concentrations (overall median of 9.86 μg m^{-3} along the whole road), compared to the other busy roads discussed previously. This may be partially due to its more open design with lower buildings and wider lane separations. Table 2 provides a breakdown of BC concentrations, categorised by the three primary roads included in the sampling route.

The BC median concentration around the radar deployed on Acevedo Dias Ave. was 5.81 μg m^{-3}. This short road segment —despite its central location— lacks bus stops and traffic lights, and buses only pass through briefly, before continuing onto 18 de Julio Ave. Vehicular traffic is limited to 620 veh. h^{-1} (point 12).

A few kilometres east of the 900-m hotspot on Rivera Ave., BC concentrations decreased and remained mostly between 7 and 14 μg m^{-3} for about 2.5 km. Traffic volume data were available for only point 16 within that transect, where a rate of 2424 veh. h^{-1} was recorded (one of the highest within the entire study area). This high traffic volume coincides with a localised area of elevated BC concentrations (14−21 μg m^{-3}) within an otherwise cleaner transect.

Given the limited availability of traffic data for a more comprehensive characterisation of Rivera Ave., we approach the discrepancies in BC concentrations along this road by examining other traffic-related factors known to influence urban air pollutant levels. The 900-m hotspot segment exhibited a significantly greater density of traffic elements. Specifically, this section contained six traffic lights and eight bus stops on both sides, compared to an average of three to five traffic lights and six to eight bus stops in adjacent segments. Whilst the number of bus stops was comparable, the reduced number of traffic lights on the cleaner sector led to fewer stops and idling, limiting the infiltration of external air into the bus cabin. This suggests that the configuration of traffic elements, particularly traffic lights in this analysis, plays an important role in determining the in-cabin BC concentrations, consistent with previous findings by Refs. [10,23,64]. Concentrations exceeding 14 μg m^{-3} were observed in a 500-m segment towards the end of the commute, likely attributable to biomass burning emissions, as indicated by a pronounced smoke odour.

We regressed the mean traffic volume at each traffic count point against the corresponding median BC concentration (Fig. 4). The analysis revealed a strong positive linear correlation, with a coefficient of determination (R^2) of 0.74. This indicates that a significant proportion of the variability in BC concentrations can be explained by variations in traffic volume. The positive trend observed aligns with existing literature [10,11], which underscores the impact of vehicular emissions surrounding buses on in-cabin air quality. Note the outlier with high traffic rate on Rivera Ave. (3459 veh. h^{-1} at point 14) but relatively low median BC concentrations, and intermediate traffic rate on 18 de Julio Ave. (2209 veh. h^{-1} at point 9), but large median BC concentrations. These observations further support the idea that traffic rate is not the sole determinant of in-cabin BC concentrations. Factors like street geometry and wind patterns also play a crucial role, as highlighted by studies such as Yang et al. [37].

3.3. Relationships with traffic attributes

To investigate the relationship between traffic attributes and BC concentrations, the pooled BC data were divided into four categories: traffic lights, bus stops, Independencia Sq. and a remaining group encompassing all other locations. Independencia Sq. was considered a distinct category due to its unique characteristics as a bus interchange point. While waiting for connecting buses at this square, BC data acquisition continued, either from the kerbside or onboard the departing bus, while it remained stationary. Consequently, this category represents a hybrid environment, combining elements of both bus stops and in-cabin exposures.

Fig. 5 compares BC concentrations in these four urban environments. The boxplots reveal substantially higher BC concentrations near traffic lights and bus stops, compared to the other locations. The traffic light group showed the highest median BC concentration (17.95 μg m^{-3}), with a range between the 5th and 95th percentiles of 33.56 μg m^{-3}, suggesting a large variability in BC concentrations. The median BC concentration near bus stops was slightly lower than at traffic lights (16.79 μg m^{-3}) with a relatively narrower 95th-5th percentile range (28.44 μg m^{-3}). The data collected at Independencia Sq. had the lowest median BC concentration (5.23 μg m^{-3}) and a 95th-5th percentile range of 20.23 μg m^{-3}. Although this square serves as a bus interchange hub, its open location promotes natural

Table 2
Descriptive statistics of BC concentrations (μg m^{-3}) for each of the three primary roads.

Road	Mean	Standard deviation	Median	Maximum	Minimum
Italia Ave.	10.91	2.72	9.86	188.07	0.41
18 de Julio Ave.	23.06	7.71	19.55	222.71	1.01
Rivera Ave.	16.79	6.69	13.36	43.78	4.36

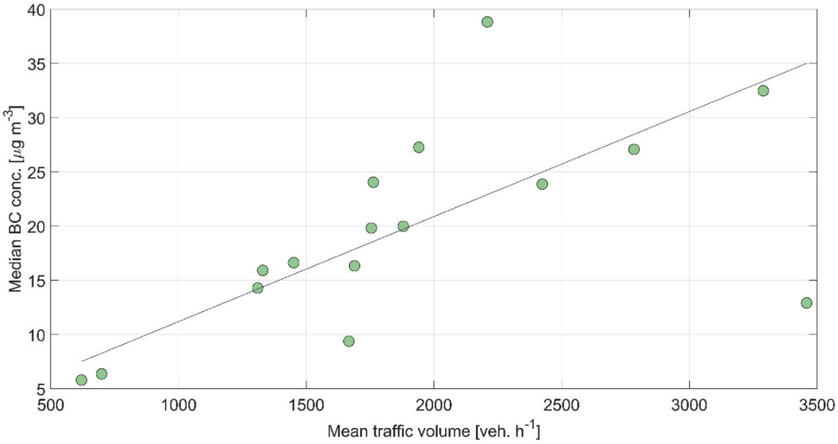

Fig. 4. Relationship between mean traffic volume and median BC concentrations.

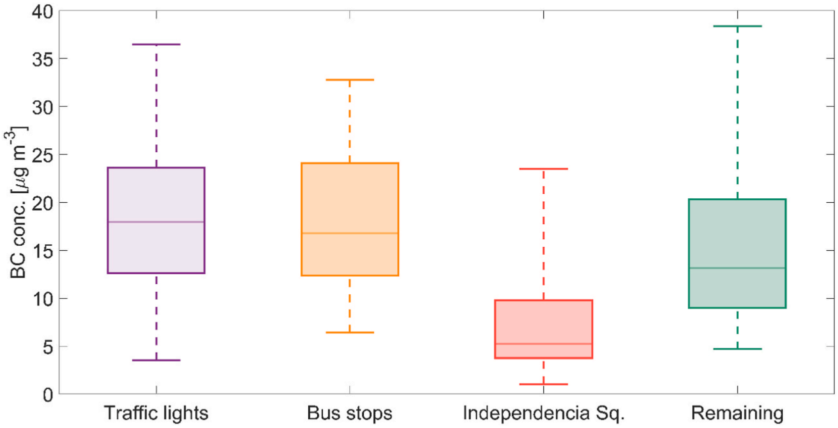

Fig. 5. BC concentrations (μg m^{-3}) in different traffic environments in Montevideo: Traffic lights, Bus stops, Independencia Sq. (bus interchange point), and Remaining locations, which encompasses all other locations along the route not included in the previous three categories. Whiskers represent the 5th and 95th percentiles.

ventilation, which contributes to the dispersion of pollutants and prevents their accumulation in the immediate vicinity. The remaining category had a median BC concentration of 13.14 μg m^{-3}, falling between the other categories. The concentrations in this category represent data points collected while buses were in motion, rather than idling. The enhanced ventilation provided by open windows during movement contributes to lower in-cabin BC concentrations [11].

To assess differences in concentrations between the four data series, the Mann-Whitney *U* test was employed with a significance level of $\alpha = 0.05$. Results indicated no statistically significant difference in BC concentrations between data collected at traffic lights and bus stops. However, pairwise comparisons between all other data series revealed significant differences, suggesting distinct patterns in their concentrations.

3.4. Spatio-temporal profile of BC concentrations

To illustrate the fine-scale patterns in BC concentrations experienced by bus passengers during their commute, we present a temporal profile of the data collected on May 13, 2019. Fig. 6 reveals strong short-term fluctuations in the BC concentrations associated with traffic-related features. Notably, BC concentrations spiked at bus stops (indicated by yellow squares) and traffic lights (blue circles), suggesting idling as a significant contributor to elevated exposure for passengers. The sharp increases at bus stops can be attributed to the infiltration of ambient air into the bus cabin as the doors open and close during passenger boarding and alighting. During these brief periods, the relatively clean interior air is exchanged with the polluted exterior environment, leading to a rapid increase in BC concentrations within the passenger compartment [11,23]. While bus stops directly introduce contaminated air through open doors, the idling periods at traffic lights also contribute to short-term spikes in BC concentrations within the bus, due to air infiltration through windows and gaps in the doors. Additionally, the absence of dedicated bus lanes in Montevideo means that buses share the road with other vehicles, amplifying the impact of emissions from surrounding traffic when bus stop at traffic lights.

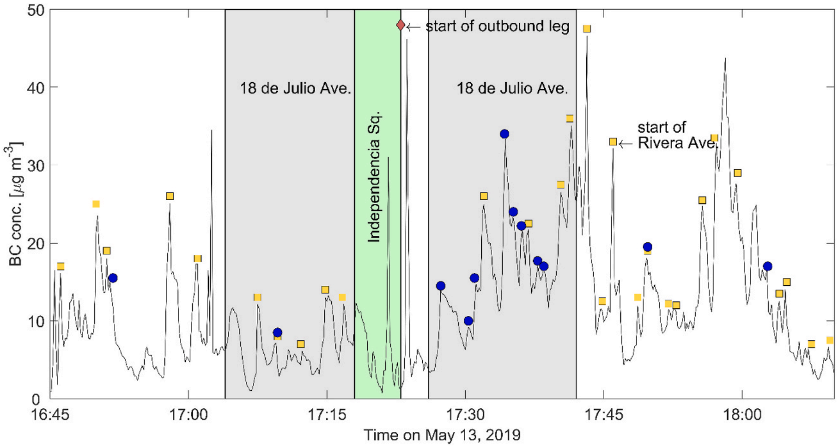

Fig. 6. BC concentrations (μg m^{-3}) during a bus commute in Montevideo on May 13, 2019. Yellow squares represent bus stops, and blue circles represent traffic lights.

BC concentrations were substantially lower when the bus travelled along 18 de Julio Ave. towards Independencia Sq. compared to the concentrations measured during the return trip (hatched grey areas in Fig. 6). Specifically, peak BC concentrations were 12.98 μg m^{-3} on the former and 33.30 μg m^{-3} on the latter (mean 6.41 μg m^{-3} *vs.* 16.15 μg m^{-3}). The observed discrepancy can likely be explained by variations in the frequency and types of stops. The inbound trip included only five stops on 18 de Julio Ave., while the outbound trip involved eight at traffic lights and four at bus stops, resulting in prolonged exposure to vehicular emissions. Additionally, the outbound bus stops were situated near intersections with traffic lights, typically with high traffic flow. It is also important to note that traffic leaving the city centre towards the periphery in the evening is generally heavier than traffic moving in the opposite direction toward Independencia Sq. Consequently, the increased number of vehicles raises emissions and elevates baseline concentrations. Combined, these factors likely contributed to increased atmospheric particle loading from surrounding traffic emissions.

4. Study limitations

This study is subject to certain limitations. Although it was conducted during a period when wood combustion is less common in Montevideo, minor contributions from residential wood burning may have influenced the overall BC concentrations, particularly when the bus passed through residential areas. A two-wavelength aethalometer would have been best suited for assessing such a confounding factor in this environment. Measuring light-absorbing carbonaceous aerosols at both ultraviolet and infrared wavelengths can help distinguish between fossil fuel and biomass burning aerosols (*e.g.*, Ref. [65]). Furthermore, the analysis did not encompass other co-pollutants known to impact human health, such as nitrogen dioxide, or additional particulate metrics, such as $PM_{2.5}$ and particle number concentrations. The latter has been included in the World Health Organization's report as a best practice statement [68]. The relatively short duration of the experiment did not capture the full range of traffic patterns, the heterogeneity of the built environment across the city and meteorological influences, such as wind speed, direction, and air temperature, which can significantly impact outdoor and, consequently, in-cabin air quality.

We did not investigate the impact of seat location on BC exposure, though previous research suggests this can significantly affect exposure levels [50]. Another limitation is the lack of analysis on how ventilation systems influence in-cabin BC concentrations, as demonstrated by Wang et al. [38]. Variations in in-cabin air pollutant concentrations may arise from a combination of factors, including the intrusion of exhaust fumes from adjacent vehicles and self-pollution originating from the bus's own exhaust emissions, as highlighted by Szyszkowicz [25] and Zhang et al. [26].

5. Conclusions

This study pioneered the first assessment of in-cabin BC concentrations aboard diesel-fuelled public buses in Montevideo, Uruguay. Our findings revealed that bus commuters in Montevideo are exposed to high BC concentrations, particularly when buses halt at traffic lights or for passenger pickups and drop-offs. The stop-and-go driving patterns and idling contributed significantly to increased exposure. The mean in-cabin BC concentration observed was 14.28 ± 14.38 μg m^{-3}, a value that is intermediate compared to other South American cities but considerably higher than levels reported in North America and Europe. Whilst urban residents spend only a small fraction of their daily activities in transport environments, the elevated BC concentrations identified in this study could lead to disproportionately high exposure doses.

The substantial variability in BC concentrations influenced by vehicular density and traffic infrastructure underscored the complexity of urban air quality along the surveyed routes. Our spatial analysis identified hotspots along major thoroughfares, notably 18 de Julio and Rivera Aves., where high traffic volumes and specific traffic configurations contributed to elevated BC concentrations. The positive correlation between traffic volume and BC concentrations highlights the need for targeted interventions to mitigate commuter exposure to air pollution. Implementing measures such as improving public transport fleet standards, optimising traffic light coordination, and reducing bus idling time could significantly reduce BC exposure.

Despite certain limitations, as described in the previous section, this research provided crucial insights into the in-cabin air quality of public buses in Montevideo. It established a baseline for future studies and emphasised the importance of improving urban transport policies to safeguard public health, particularly in regions heavily reliant on diesel-powered public transportation.

To further advance knowledge in this field, future studies could refine the current research by i) examining the seasonal variability of in-cabin BC concentrations; ii) including other particulate metrics (*e.g.*, $PM_{2.5}$ and particle number concentrations); iii) extending the measurements scope to encompass neighbourhoods with diverse traffic attributes and built environment and iv) exploring the impact of different bus models, fuels, maintenance practices and ventilation conditions. Lastly, considering the widespread practice of wood burning for residential heating in Montevideo, using a two-wavelength aethalometer would be advantageous for differentiating between BC originating from fossil fuels and wood combustion.

CRediT authorship contribution statement

Admir Créso Targino: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Camila Couto da Costa:** Visualization, Software, Investigation, Formal analysis, Data curation. **Patricia Krecl:** Writing – original draft, Supervision, Methodology, Investigation.

Data availability

Data will be made available on request. For requesting data, please write to the corresponding author.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Admir Créso Targino and Patricia Krecl report a relationship with Heliyon that includes: board membership. The first author is Section Editor for Heliyon Environment. The other 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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