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Research Article

Personal Exposure to $PM_{2.5}$ in the Massive Transport System of Bogotá and Medellín, Colombia

Maria Paula Castillo-Camacho[1)], **Isabel Cristina Tunarrosa-Grisales**[1)], **Lina María Chacón-Rivera**[1)], **Marco Andrés Guevara-Luna**[2),3),4)], **Luis Carlos Belalcázar-Cerón**[2),*]

[1)]Environmental Engineering Program, Sergio Arboleda University, Bogotá, Colombia
[2)]Universidad Nacional de Colombia, Departamento de Ingeniería Química y Ambiental, Bogotá, Colombia
[3)]Smart and Simple Engineering, Research Department, Bogotá, Colombia
[4)]Conservación, Bioprospección y Desarrollo Sostenible (COBIDES), Universidad Nacional Abierta y a Distancia, Escuela de Ciencias Agrícolas, Pecuarias y del Medio Ambiente (ECAPMA), Bogotá-Colombia

***Corresponding author.**
Tel: +(57-1) 3 16 50 00; Ext. 14094
E-mail: lcbelalcazarc@unal.edu.co

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ABSTRACT Recent studies have shown that public transport users can be exposed to high levels of pollution emitted from their own vehicles and nearby sources. The purpose of this research is to determine the personal exposure of passengers to $PM_{2.5}$ inside the vehicles of the massive public transport of two of the main and more populated cities of Colombia, Bogotá and Medellín. TM (TransMilenio powered by diesel) and SITVA (electric and gas natural vehicles) were the systems studied. Were evaluated the integration of new vehicles with technologies Euro V and Euro VI in the TM system, the impact of the weekend effect on personal exposure into public transport (TM and SITVA), and the possible differences between personal exposure regarding the ways of the systems (mixed lane or exclusive lane for TM and SITVA). To measure $PM_{2.5}$ levels, a DustTrak monitor previously calibrated was used. This measurement campaigns lasted for more than 80 hours and a mean of 17000 data of $PM_{2.5}$ concentrations were obtained for each route. The personal dose was calculated based on the recorded data. The mean $PM_{2.5}$ concentrations and personal dose found in the research for TM are 167 μg/m^3 and 2.3 μg/min, respectively, while, for SITVA they are 41 μg/m^3 and 0.53 μg/min, respectively. Therefore, SITVA users have a 5 times lower personal exposure to $PM_{2.5}$ than TM users. It was also found that due to the poor proportion of new TM vehicles during the monitoring period, the personal exposure in the old vehicles and in the new ones is similar. In the case of SITVA, it was evidenced that the mixed lane contributes to a high personal exposure to $PM_{2.5}$ than the exclusive one.

KEY WORDS Particulate matter, Personal exposure, Air quality, Public transport systems, Self-contamination

1. INTRODUCTION

Air pollution is one of the biggest environmental problems worldwide today. Poor air quality causes about 4.2 million premature deaths annually, and 91% occur in developing countries (WHO, 2018). The main cause of these deaths is attributed to personal exposure to Particulate Matter of 2.5 microns or less ($PM_{2.5}$). The WHO (2005) warns that by inhaling this type of particles constantly, the risk of lung, cardiovascular and ischemic diseases increases. Based on evidence of the effects on health of the exposure to $PM_{2.5}$, the WHO has established a maximum safe level of exposure of 25 μg/m^3 $PM_{2.5}$ for an average of 24 hours and 10 μg/m^3 $PM_{2.5}$ for annual average.

Personal exposure is defined as the event in which a person comes into contact with an air pollutant. In other words, it can be understood as the measurement by a monitor of a pollutant of interest near a person's breathing zone (Steinle *et al.*, 2011). Studies worldwide have reported that one of the most important air pollutants to which citizens are exposed is $PM_{2.5}$, from which 30% is attributed in urban centers to be emitted by different means of transport fueled with fossil fuels (Krzyzanowski *et al.*, 2005). For this reason, it is relevant to evaluate the impact of the means of transport regarding personal exposure to pollutants. Additionally, some studies have determined various factors that condition this exposure. These factors can correspond to external variables of the city, such as road structure, traffic density, time of day and weather, or to internal conditions, such as the characteristics of the vehicle in terms of fuel type, technology, emission standards and ventilation system (Nazelle *et al.*, 2017).

Li *et al.* (2015) evaluated the personal exposure to $PM_{2.5}$ and Black Carbon in different transport scenarios in Shanghai. They found that diesel vehicles are significant sources of polluting emissions and that the doses inhaled on these buses are higher compared to other means of transport. A study in Santiago de Chile by Suárez *et al.* (2014) found that the average concentration of $PM_{2.5}$ (17.5 μg/m^3) is higher in diesel buses than in other means of transport evaluated, generating an exposure 8 times higher than in private cars and 0.4 times more than in bicycle. Similarly, in Barcelona, Moreno *et al.* (2015) compared personal exposure to $PM_{2.5}$ in various means of transport and found that the concentrations of $PM_{2.5}$ in diesel buses are 56% higher than in the tram, which had the least exposure.

On the one hand, in Bogotá, exposure to $PM_{2.5}$ has been researched in the mass transit system TM (TransMilenio), which is one of the largest public transport systems with rapid transit buses (BRT) in the world and whose buses use diesel fuel with technologies Euro II, III and IV. Morales *et al.* (2017) determined that the exposure and inhalation dose of fine particles of $PM_{2.5}$ is higher within the TM system, compared to other means of transport that include active modes such as cycling and walking. Additionally, Morales *et al.* (2019) found that in TM the dose of $PM_{2.5}$ exceeds 1.2 times the one suggested by the WHO, and Euro II and III vehicles had twice the exposure of this pollutant than in the stricter Euro IV or higher standards.

The high exposure levels to $PM_{2.5}$ are associated with self-contamination processes. According to Guevara (2018), this phenomenon represents an average of 20% and a maximum of 70% of the presence of $PM_{2.5}$ inside the BRT for TM vehicles, while the remaining percentage corresponds to emissions from other nearby sources. The TM system has decided to gradually integrate buses with Euro V and VI standards (Transmilenio, 2019) that are expected to reduce emissions of these particles and improve exposure conditions and doses of $PM_{2.5}$ in the system.

On the other hand, Medellín has the integrated public transport system for the Aburrá Valley (SITVA), which is constituted by Metro, Tram and Metrocable, which use electricity as an energy source, while BRT buses of this system run with compressed natural gas (CNG). Since Medellin has an integrated low emission system, low levels of personal exposure to $PM_{2.5}$ are expected. However, there are still no studies that evaluate the exposure and potential dose for passengers of these means of transport, nor previous researches comparing this system with the TM system of Bogotá or with other means of mass public transport.

The objective of this study is to determine the levels of personal exposure to $PM_{2.5}$ by users of the Bogotá and Medellín mass transit systems and identify the segments where there is greater exposure to $PM_{2.5}$ in these systems. Some specific scenarios are also evaluated, such as the introduction of Euro V vehicles in the TM fleet, the impact of the mixed lane on the path of the BRT Line 2 of the SITVA and the implications of the weekend effect on some routes of both systems.

2. METHODOLOGY

2. 1 Massive Transport System of Bogotá and Medellín

TM is the massive transport system of Bogotá that started operations in the city in the 2000, with only 14 BRT vehicles in its first three trunk lines, AutoNorte, Calle 80, and Avenida Caracas, that comprised the Phase I. Between 2001 and 2003, other four trunk lines that comprised Phase II were built: Américas, NQS,

Table 1. Description of the trunk lines of TM evaluated on the research, Alcaldía Mayor de Bogotá (2016) and TM (2018).

Trunk line	Power source	Length	Daily average users	Phase	Start year
Calle 80	Diesel	10.1 km	40000	I	2000
Caracas (Héroes - Tercer Milenio)	Diesel	8.3 km	60000	I	2000
AutoNorte	Diesel	11.8 km	95000	I	2000
NQS (NQS + AutoSur)	Diesel	22.9 km	60000	II	2001-2003
Calle 26	Diesel	12.2 km	34000	III	2012

Table 2. Description of the SITVA. Information taken from AMVA (2019).

Transport mode	Power source	Length	Daily average users	Start year
Metro	Electric	31.3 km	800000	1995
Metrocable	Electric	11.9 km	41000	2004
Tramcar	Electric	4.3 km	45000	2016
Metroplús BRT	Compressed natural gas (CNG)	26.0 km	125000	2011

AutoSur, and Avenida Suba. Finally, Phase III was delivered in 2012, which is constituted by Calle 26, Carrera 10, and Calle 6. Nowadays, the system has a length of 114.4 km, 12 trunk lines, 9 portals, and 139 stations (TansMilenio, 2018b). For this research, six trunk lines were considered, as described in Table 1.

In Medellín, the SITVA was created with the purpose of being a strategic transport system with different modes adapted to the morphologic conditions of the city. This transport modes are Metro, Metrocable, Tranvía, and BRT. The description of this system is shown in Table 2.

2.2 Monitoring

Near 80 hours of $PM_{2.5}$ measurement and monitoring campaigns were performed into the massive transport vehicles of TM and SITVA. In Bogotá, the campaign was done in the trunk lines Calle 80, Caracas, AutoNorte, NQS, Calle 26, and AutoSur. In Medellín, the campaign was in the whole multimodal SITVA system.

$PM_{2.5}$ concentrations were measured with two aerosol monitors DustTrack (DRX 8533EP and 8530EP), which were calibrated previously to ensure a correct operation and accurate results. The 2.5 microns filter was chosen, as it is the size of the particulate matter for the research. The monitors were put at chest height with the purpose of obtaining a similar catching to the input air in the breathing process. It was set in a sampling interval between 1 and 15 seconds. Monitoring was done in high and low user flow schedules to ensure a suitable rendering. The geolocation was also recorded during the journeys by the app MyCarTracks, with an accuracy of 10 meters and time intervals of 10 seconds. Additionally, a field record was kept to identify the monitor work into the vehicles or out of them, the start and end time of journeys and relevant punctual events that could have an impact on the $PM_{2.5}$ concentration.

DustTrak measures the particulate matter concentration by 1 hz photometry process, it has a wavelength of 780 nm, taking samples continuously. Measurement is done by an impact with a chosen particle size of 2.5 microns in this case. Then, these particles pass through the monitor by the action of a suction pump (TSI Incorporated, 2012).

The details of the monitoring campaigns in Bogotá and Medellín are shown at Tables 3 and 4.

In Bogotá, the monitoring campaign was developed measuring $PM_{2.5}$ concentrations into different vehicles of the system that were chosen randomly in each of the trunk lines. Measurements were done at the middle and back corners of the buses. The monitoring lasted for four weeks, two days for each trunk line and with an average of four hours per day, in schedules between 9 to 13 and 14 to 19 hours, getting close to 88000 data points for personal exposure to TM. The measurements were performed in two different periods: the first one from May to June of 2018, which is a rainy season, and the second one from April to May of 2019, which is a rainy season too, according to the Instituto Colombiano de Hidro-

Table 3. Monitoring campaign in TM, Bogotá.

Trunk line	Campaign dates	Journey	Measuring duration (min)	Technology of vehicles
Calle 26	Wednesday 23/05/2018 Thursday 24/05/2018	Universidades station - Portal El Dorado	209 200	Euro II, III, IV
Calle 80	Monday 28/05/2018 Wednesday 30/05/2018	Polo station - Portal 80	177 183	Euro II, III, IV
Caracas	Friday 25/05/2018 Saturday 26/05/2018	Héroes station - Tercer Milenio	208 182	Euro II, III, IV
Autopista Sur	Tuesday 05/06/2018 Thursday 07/06/2018	Comuneros station - Portal Sur	178 126	Euro II, III, IV
AutoNorte NQS-AutoSur	Wednesday 03/04/2019 Thursday 11/04/2019 Friday 03/05/2019 Monday 06/05/2019 Tuesday 07/05/2019	Portal Norte - Portal Sur	102 99 115 204 170	Euro IV
AutoNorte NQS-AutoSur	Friday 03/05/2019 Tuesday 07/05/2019 Wednesday 08/05/2019 Thursday 09/05/2019	Portal Norte - Portal Sur	54 45 43 216	Euro V

logía, Meteorología y Estudios Ambientales (IDEAM). During the journeys, the license plate and serial of each monitored vehicle were registered, identifying the journeys with start and end hour, and the relevant events that happened in the way.

It is important to highlight the vehicles technologies of TM where the personal exposure was evaluated, considering that is a system with diesel ACPM Euro II and Euro III as power source in Phases I and II (Departamento Nacional de Planeación, 2008). For Phase III, the diesel used is technology Euro IV. The vehicles monitored were 39 in total, from which 30 of them have Euro II, III and IV technology and the remaining 9 have Euro V technology.

In Medellín, the monitoring campaign was done for 10 days, completing about 30 monitoring hours, the measurement was made taking random positions into the vehicles. The schedule also took into account high and low users flows, between 9 to 18 hours, with an average length of 6 daily hours, getting near to 77000 data points. The first monitoring season was on January of 2019, in dry season, and the second season was on April 2019, in rainy season according to the IDEAM, 2019.

The measuring campaign was developed during the time periods detailed in Table 3 and Table 4 because of the availability of the equipment and logistics, the measurements were performed during dry days. It will be interesting for future research to develop measurements in days different seasons. Even so, the results obtained in this research were developed in dry days.

During the journeys, the vehicles identification was registered as well as the start and end time, journeys description and relevant events that happened in the journeys. According to this the data of the trips were recorded and can be summarized as: average percentage of occupancy inside the vehicles (60% in TM and 50% in SITVA), average ventilation in terms of window opening level (90% in TM and SITVA) with the exception of the hybrid-hermetic buses of SITVA (0%).

2.3 Specific Scenarios

Some of the collected data during the monitoring campaigns were used to evaluate three particular scenarios of interest for this study, such as the weekend effect, the impact of the BRT bus fleet renewal in Bogotá, and the impact of the exclusive lane in contrast to a mixed lane found in the BRT system in Medellín. To evaluate the weekend effect, weekdays and Saturdays were monitored on the same BRT route. In Bogotá, this

Table 4. Monitoring campaign in SITVA, Medellín.

Mean of transport	Monitoring dates	Journey	Id transport	Measuring duration (min)
Metro	Wednesday 09/01/2019	La Estrella - Niquía.	Línea A.	98
	Friday 11/01/2019	La Estrella - Niquía, San Antonio - San Javier.	Línea A. Línea B.	90
	Monday 14/01/2019	La Estrella - Niquía, San Antonio - San Javier.	Línea A. Línea B.	169
	Wednesday 16/01/2019	La Estrella - Niquía.	Línea A.	155
	Thursday 17/01/2019	La Estrella - Niquía, San Antonio - San Javier.	Línea A. Línea B.	106
	Wednesday 17/04/2019	San Antonio - San Javier.	Línea B.	31
Metrocable	Saturday 12/01/2019	Oriente - Villa Sierra	Cable H	19
	Monday 14/01/2019	Oriente. San Javier. Santo Domingo	Cable H, Cable J, Cable K	89
	Wednesday 16/01/2019	Acevedo - Santo Domingo	Cable k	184
	Thursday 17/01/2019	Oriente. San Javier. Santo Domingo	Cable H, Cable J, Cable K	106
	Wednesday 17/04/2019	Oriente - Villa Sierra	Cable H	38
Tramcar	Saturday 12/01/2019	Oriente - San Antonio	TA	55
	Monday 14/01/2019			40
	Thursday 17/01/2019			78
	Wednesday 17/01/2019			20
BRT vehicle L1	Tuesday 15/01/2019	Línea 1 BRT	L1	192
	Friday 18/01/2019			82
BRT vehicle L2	Thursday 10/01/2019	Línea 2 BRT	L2	245
	Tuesday 15/01/2019			203
	Friday 18/01/2019			122

evaluation was done on the Troncal Caracas and in Medellín on the tramcar.

In Bogotá, the gradual renovation of the TM BRT bus fleet is under way. The renovation consists in the replacement of the Euro II, Euro III, and Euro IV technology buses, with Euro V and Euro VI technologies buses. To evaluate the impact of this renovation, monitoring was carried out on the AutoNorte, NQS, AutoSur, on Euro IV technology buses and on some of the first Euro V new buses implemented in the system.

The line 2 BRT buses of Medellín circulate through an exclusive lane in a 7 km section, while in this same line, buses must share the road with other vehicles such as cars, trucks, motorcycles, among others, in a section of 5.5 km. To assess the impact that the type of lane has on personal exposure within buses, location data was used to separate the data recorded in the exclusive and mixed lane sections. In all scenarios, the evaluation is performed by comparing the concentrations recorded in each case.

2.4 Data Analysis

With the monitoring campaigns, a database consisting in the concentration of $PM_{2.5}$ and location was created for each evaluated path. Data analysis was developed using different computational tools. Through the Rstudio® interface, a statistical and graphic analysis was done applying position measurements for ungrouped data of all the concentration obtained in each of the monitoring sessions.

With the ArcGIS® program, the geospatial analysis of the personal exposure was carried out, in which the $PM_{2.5}$ concentration database and location database was loaded and visualized for each route of the different transports. Based on a base map of the cities of Bogotá and Medellín, concentration mapping was established in a scale system consisting of four chromatographic divisions. This classification was based on the trend of concentration levels obtained during the monitoring, starting with the suggested level by the WHO from 0–25 μg/m^3 $PM_{2.5}$. In this way, the critical points of exposure to $PM_{2.5}$ are determined geographically.

The calculation of the average doses of $PM_{2.5}$ was developed for each path studied, implementing the formula of the potential inhaled dose (equation 1) proposed by Morales *et al.* (2017). This formula represents the pot-

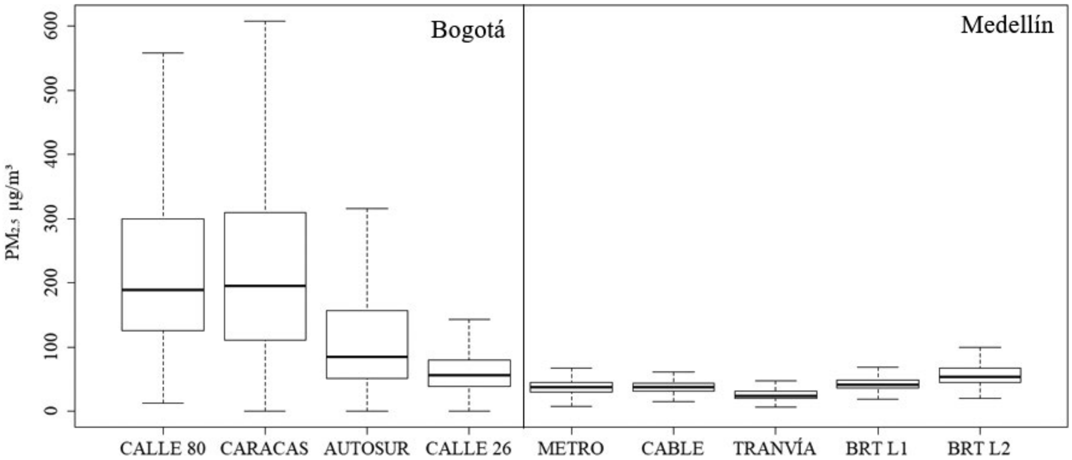

Fig. 1. $PM_{2.5}$ measured concentrations in TM and SITVA.

ential dose of an inhaled contaminant by a person during a trip, from the starting point to the end point of the journey, integrating to the formula the exposure concentration, the inhalation rate associated with the type of transport and the duration of exposure.

$$D = C_{PM2.5} \times IR \times \Delta t \tag{1}$$

where D is the potential dose of $PM_{2.5}$ inhaled by a person (in units of mass), $CPM_{2.5}$ is the average concentration of $PM_{2.5}$ obtained (units of mass over volume), IR is equal to $1.30 \times 10^{-2}\ m^3/min$, which refers to the average inhalation rate for public transport users, considering a light level of activity, according to Morales (Morales *et al.*, 2017) and based on standards defined by the Environmental Protection Agency (EPA). Finally, Δt is the duration of the exposure in minutes.

Additionally, to facilitate the performance of a standard analysis, the normalization of the calculation in relation to the unit of time is proposed, through the implementation of equation 2.

$$D_t = D/\Delta t \tag{2}$$

Where D_t is the potential dose per unit of time, D is the formula for potential dose and Δt is the duration of exposure in minutes.

3. RESULTS AND DISCUSSION

3.1 Concentrations of Exposure to $PM_{2.5}$ in TM and SITVA

The data obtained from $PM_{2.5}$ measurements into TM buses that were 80% Euro II and III technologies show a data distribution with large concentration differences in the trunk lines (Fig. 1). Caracas and Calle 80 had the higher $PM_{2.5}$ personal exposure, since their exposure is 4 and 3 times, respectively, greater than in Calle 26, which had the lower exposure. The mean concentrations found in the monitoring were 246 µg/m³ (Caracas), 223 µg/m³ (Calle 80), 131 µg/m³ (Autopista Sur), and 69 µg/m³ (Calle 26).

The maximum concentrations shown in Table 5 exceed the limits of the boxplots because these points of data are outliers that can refer to punctual events or zones that present high concentrations of $PM_{2.5}$ and do not meet the frequency characteristics that were used for the boxplot design.

The concentrations found into the SITVA are shown in Fig. 1. The transport means with electric power and relative zero emissions such as metro, Metrocable and tramcar had $PM_{2.5}$ average concentrations of 38 µg/m³, 39 µg/m³, and 28 µg/m³, respectively. These concentrations are lower than the $PM_{2.5}$ concentrations found into the BRT system, which is powered with GNC and presented 45 µg/m³ $PM_{2.5}$ to line 1 and 61 µg/m³ $PM_{2.5}$ to line 2. The lowest personal exposure found in the SITVA was into the tramcar, while the BRT system had 2 times higher exposure than metro and Metrocable, which were exposed 73% more than the tramcar.

According to this outlines (Table 5), Line 2 of BRT presents a larger record of this data than the others microenvironments analyzed, due to the interaction with mix lanes in its journey, having greater exposure to external sources. Metro, Metrocable and tramcar have

Table 5. $PM_{2.5}$ concentration data in the massive transport systems of Bogotá and Medellín.

Bogotá	Average concentration ($\mu g/m^3$)	Standard deviation	Max concentration ($\mu g/m^3$)	Total data	Total outline	% Outline
Caracas	246	223	3100	18073	1813	10%
Calle 80	223	205	4690	21720	1265	5, 8%
AutoSur	131	127	975	23401	1291	5, 5%
Calle 26	69	53	669	25105	1836	7, 3%
Medellín						
Metro	38	11	211	27427	471	2%
Cable	39	11	121	8880	611	7%
Tranvía	28	14	221	10465	684	7%
Línea 1	45	16	448	10603	669	6%
Línea 2	61	28	510	14675	1183	8%

better personal exposure because of their controlled ventilation and exclusive lanes.

The statistical analysis of both studied cities show a pattern of the dispersion of pollutants in the vehicles. In Medellín, the values are more uniform and considerably lower than the exposure in TM. $PM_{2.5}$ average concentration in TM is 167 $\mu g/m^3$, which is 4.7 times higher than the average concentration in SITVA (41 $\mu g/m^3$). The SITVA has maximum concentrations of about 500$\mu g/m^3$, while in TM they are maximum 5000 $\mu g/m^3$, which is 10 times higher than the SITVA.

Different research around the world in various cities have evaluated the personal exposure to $PM_{2.5}$ in their transport systems. It has been found that the BRT diesel powered the higher personal exposure system. According to the present research, $PM_{2.5}$ monitoring campaigns done in Guangzhou (China), Dublin (Ireland), and Jakarta (Indonesia) show similar average concentrations to those found in Bogotá in different studies, such as 167 $\mu g/m^3$ (Castillo *et al.*, 2019), 164 $\mu g/m^3$ (Guevara, 2018), and 186 $\mu g/m^3$ (Morales *et al.*, 2017), which is the first approximate to 150 $\mu g/m^3$. Similarly, exposure in BRT has also been evaluated in principal cities like Boston (U.S.A.) and Hong Kong (China) and showed average concentrations of about 100 $\mu g/m^3$, while Florencia (Italia) had 50 $\mu g/m^3$ close to the 53 $\mu g/m^3$ $PM_{2.5}$ found in Medellín (Castillo *et al.*, 2019). However, European cities like Milan (Italia), London (United Kingdom), and Helsinki (Finland), had average concentrations of about the 25 $\mu g/m^3$ suggested by the WHO (Kumar *et al.*, 2018).

Another research that evaluates the $PM_{2.5}$ concentration in the elevated railway in the cities of Los Angeles (United States), Naples (Italy), and Taipei (Taiwan) presented average concentrations of 14 $\mu g/m^3$, 13 $\mu g/m^3$ (Cartení *et al.*, 2015), and 19 $\mu g/m^3$ (Cheng *et al.*, 2012), respectively. Similarly, the subway system in London (England) had average concentrations of 29 $\mu g/m^3$ in its elevated route (Cartení *et al.*, 2015), closer to that presented in Medellin (38 $\mu g/m^3$). These lower concentrations presented in the elevated routes are due to ventilation inside of the vehicles and the external air interaction free of pollution sources (Cartení *et al.*, 2015).

3.2 Spatial Distribution of $PM_{2.5}$ TM and SITVA Journeys

The $PM_{2.5}$ concentration data spatially represented for TM (Fig. 2a) demonstrates the high exposure by observing values greater than 100 $\mu g/m^3$ on the Calle 80 (Portal 80 header) and Caracas (Heroes-Tercer milenio) ways, followed by the AutoSur (Portal South header). Calle 26 (El Dorado-Universidades) maintains concentrations of less than 100 $\mu g/m^3$ throughout its route, with very little excess of this concentration.

One of the main reasons that explain this distribution is the structure of the roads where the TM and SITVA are located. Regarding mainly the transverse amplitude of the roads along the way, the distribution can be observed in Table 6.

One of the characteristics that make a road open is the wide distance between sidewalk and sidewalk, favoring the ventilation process by dispersing the concentration of contaminants (Pachón *et al.*, 2018). For this reason, according to Table 6, it becomes clear that the Caracas

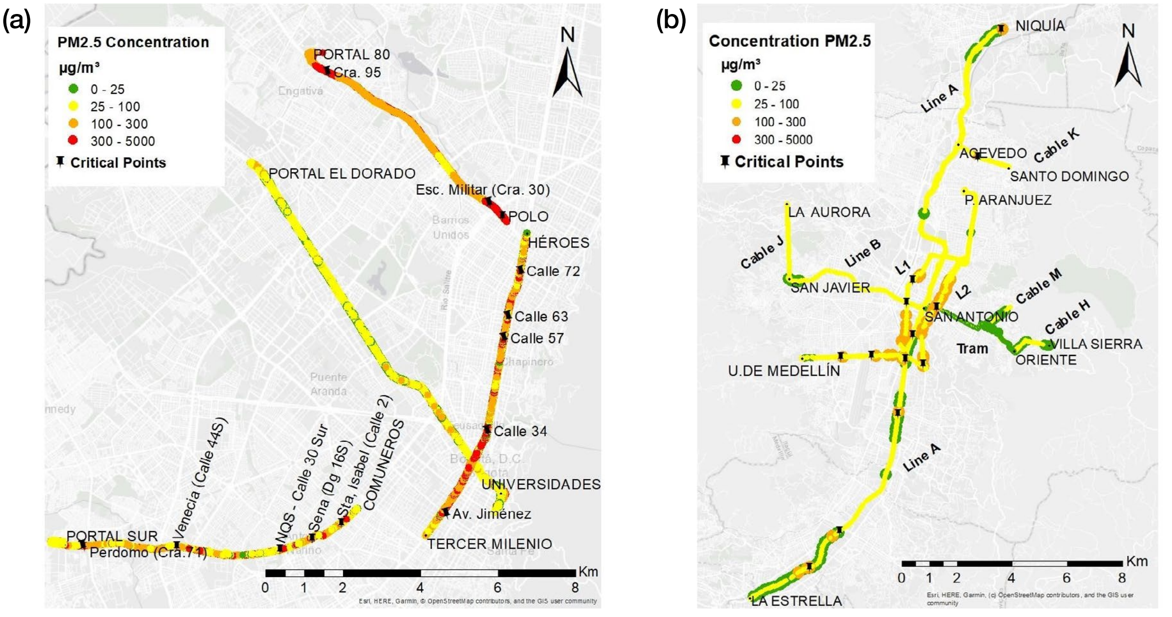

Fig. 2. Spatial distribution of $PM_{2.5}$ in (a) TM and (b) SITVA $PM_{2.5}$.

and Calle 80 have less amplitude than AutoSur and Calle 26, which additionally have higher density of buildings in quantity and in height. This amplitude factor is considered as one of the main reasons for the high presence of $PM_{2.5}$ and the high number of critical points in these two trunklines. Additionally, it is possible to emphasize that, besides to the great amplitude of Calle 26, this road presents green corridors almost all along its entire route between the mixed traffic lanes, which contributes to the decrease of $PM_{2.5}$ present in route.

The critical points shown in Fig. 2a have common characteristics that favor the presence of $PM_{2.5}$ in the microenvironment of the TM system. These factors refer to the high presence of heavy traffic fueled with diesel and with low emissions control (Ramírez, 2018), the nearby industrial corridors and several strategic points for city mobility, where important high traffic avenues meet.

Different studies have shown that diesel vehicles emit 4 times more $PM_{2.5}$ than gasoline vehicles (Rojas, 2004). In Bogotá, public buses, TM, and heavy traffic are powered by diesel (Ramírez, 2018). Under these conditions, circulating along the ways of the TM system or nearby generates high exposure to $PM_{2.5}$. Besides, the number of TM buses with technologies below Euro V is numerous, contributing with high concentrations among the vehicles of the system. This concentrations are about 80% (Guevara, 2018) and the remaining proportion occurs due to self-pollution.

The geospatial characterization of the obtained concentrations for Medellín transport system observed in Fig. 2b evidences different levels of exposure to $PM_{2.5}$, mostly less than 100 $\mu g/m^3$. Elevated metro line A carries out routes from La Estrella station to Niquía. This route shows concentrations below 25 $\mu g/m^3$ in journeys between stations located outside the city center due to the decrease in emissions in these areas. The points of line A with concentrations greater than 100 $\mu g/m^3$ are found at the Itagüí, Envigado, El Poblado and Niquía stations. The high population density of Itagüí and Envigado have influenced the growth in the demand for services in these municipalities (Alcandía de Medellín, 2016), generating contributions of greater concentration of exposure to $PM_{2.5}$. The metro line B that runs from San Javier station to San Antonio has concentrations in ranges of 25 $\mu g/m^3$ and 100 $\mu g/m^3$, as in line A, which is an effect of the city air quality. In the vicinity of San Javier station, concentrations are below 25 $\mu g/m^3$ (Fig. 2b).

The San Javier – La Aurora metrocable line (Cable J) is exposed to similar concentrations to those of the Acevedo – Santo Domingo (Cable K), with concentrations below 100 $\mu g/m^3$ and an average of 39 $\mu g/m^3$. A critical point is observed in the cable K route due to an increase in the concentration of the Andalucía station, due to the

Table 6. Amplitude of the road characteristics.

Road	Average transverse amplitude	Surrounding lanes of mixed traffic
Caracas	35 meters	2
Calle 80	45 meters	3–4
AutoSur	49 meters	4–5
Calle 26	95–100 meters	5–6

Table 7. Average $PM_{2.5}$ concentrations and dose in TM and SITVA.

Bogotá	Average concentration ($\mu g/m^3$)	Average time in system (min)	Inhaled dose by journey (μg)	Average dose by time ($\mu g/min$)
Calle 80	223	20	57.9	2.9
AutoSur	131	20	34.0	1.7
Caracas	246	30	95.9	3.7
Calle 26	69	20	17.9	0.8
Medellín				
Metro	38	45	22.2	0.49
Metrocable	38.5	30	15.0	0.50
Tramcar	28	20	7.2	0.36
Line 1	44.5	42	24.3	0.57
Line 2	60.6	84	66.2	0.78

crossing of existing urban traffic roads under this line. The behavior of $PM_{2.5}$ concentrations in cable lines is similar to the average metro concentrations (Fig. 2b) because these two means (metro and cable) operate almost as isolated systems during movement and have exclusivity in their perimeter of operation.

In contrast, the tramcar has exposures of concentrations lower than 25 $\mu g/m^3$ in a generalized way along its routes from San Antonio station to Oriente station. The tramway lane is not influenced by near emissions of vehicular traffic since it is mostly surrounded by pedestrian paths, with a controlled ventilation system inside the cars that favors the air quality in the microenvironment.

As shown in Fig. 2b, the BRT systems that operate with gas are in Line 1, from Universidad de Medellín to Parque Aranjuez in an exclusive lane. Line 2 takes part of this route in the exclusive lane of the system and changes to a mixed lane when the bus arrives at the city center. The two bus lines have a general exposure to concentrations below 100 $\mu g/m^3$ when they are outside the central area of the city. In contrast, when arriving at the center, exposure to $PM_{2.5}$ can increase up to 300 $\mu g/m^3$ due to the influence of traffic on the surrounding roads and the industrial and commercial activity of this area. Additionally, the two lines have a more favorable behavior towards the periphery with concentrations less than or equal to those suggested by the WHO standard (2005).

3.3 Potential Inhaled Dose of $PM_{2.5}$ Exposure

Table 7 shows the average $PM_{2.5}$ dose and concentration calculated in TM and SITVA. In TM, Caracas trunkline presented the highest dose in all the system (3.7 $\mu g/min$), while Calle 26 had the lowest dose with 0.8 $\mu g/min$. As discussed in section 3.2, the main reasons for this situation is that Avenida Caracas is characterized by being a narrow track surrounded by buildings with average height ratio of 20 m and width of 35 m. In contrast, the Calle 26 has a track average width of 100 m and green corridors which facilitate the ventilation process and improve the dispersion of pollutants. Additionally, in the Caracas Avenue there are still old TM vehicles circulating with poor technologies, whilst in the Calle 26 there are newer and better BRT technology (Guevara *et al.*, 2020).

In Medellín SITVA, the highest $PM_{2.5}$ dose are found in Line 1 and Line 2 BRT system (0.57 and 0.78 $\mu g/min$). The electric power systems have lower doses than

Table 8. Specific scenario statistics.

	Monitoring time (min)	Average concentration (μg/m^3)	Average dose (μg/min)	Standard deviation	Maximum concentration (μg/m^3)
Weekend effect trunk line Caracas Bogotá (1 pm–7 pm)					
Friday	208	286	3.7	255	3100
Saturday	182	203	2.6	171	1670
Decrease		29%	30%		46%
Weekend effect Tramcar Medellín (10 am–2 pm, 5 pm–6 pm)					
Week	138	30	0.4	9	203
Saturday	55	23	0.3	6	80
Decrease		23%	25%		61%
Pilot test EURO V TM (9:30 am–5 pm)					
Old TM (Euro IV)	358	116	1.5	52	508
New TM (Euro V)	690	106	1.4	71	805
Decrease		9%	7%		−58%
Fleet renewal TM Initial stage					
Old TM					
New TM					
BRT line 2 Mixed lane (10:30 am–5 pm)					
Mixed lane	312	80	1.1	33	396
Exclusive lane	257	44	0.6	12	128
Decrease		45%	46%		209%

BRT. The found doses are higher in Metrocable with 0.50 μg/min than metro and tramcar, which have personal exposures of 0.49 μg/min and 0.36 μg/min, respectively.

When comparing the calculated dose in TM system and SITVA, it is found that the TM dose is 4 times higher than the personal exposure in SITVA. When compared with the OMS concentration dose suggested, both systems exceed the average 25 μg/m^3 $PM_{2.5}$ in 24 hours. SITVA is twice that dose and TM is 7 times higher. Applying the dose estimation by time of the OMS regulation, this dose is 0.38 μg/m^3, and it is exceeded by all mean transports, except for the tramcar of SITVA.

3.4 Scenario Analysis

3.4.1 Weekend Effect Trunkline Caracas

The average concentration found on Friday was 29% higher than the one measured on Saturday. Likewise, the maximum concentration on Friday was twice higher than the one measured on Saturday and the Friday $PM_{2.5}$ dose is 30% higher than the Saturday dose (Table 8).

In Fig. 3, the difference between personal exposure to $PM_{2.5}$ on Friday and Saturday can be observed. The decrease presented on Saturday is evident, mainly at critical points on Friday that exceeded 300 μg/m^3. On Saturday, there are much less values higher than 300 μg/m^3, and this can be attributed to a decrease in urban activity and the change of surrounding traffic density.

3.4.2 Weekend Effect in the Tramcar of SITVA

Table 8 presents the measured concentrations on weekdays and saturday, where it is remarkable the decrease of $PM_{2.5}$ concentrations in doses on Saturday of 23% and 25%. Saturday is considered as an atypical day because of the weekend effect that refers to a decline and change of anthropogenic activities on Saturdays and Sundays, especially in urban zones. $PM_{2.5}$ concentration is reduced due to the low presence of $PM_{2.5}$ sources such as private traffic and load diesel vehicles, and to urban activity in the central and perimeter zones between San Antonio and Bicentenario stations (Franco and Parra,

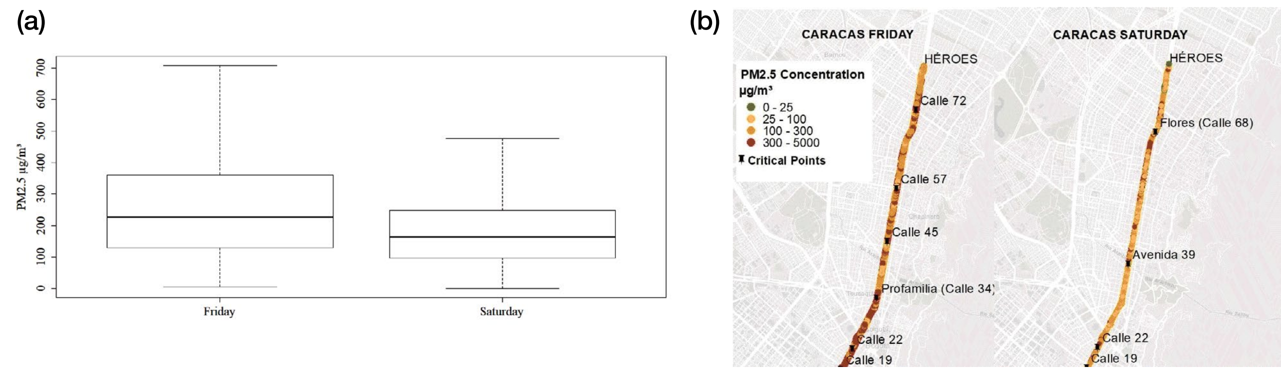

Fig. 3. (a) Boxplot and (b) Spatial representation of the weekend effect in the Caracas trunkline of TM.

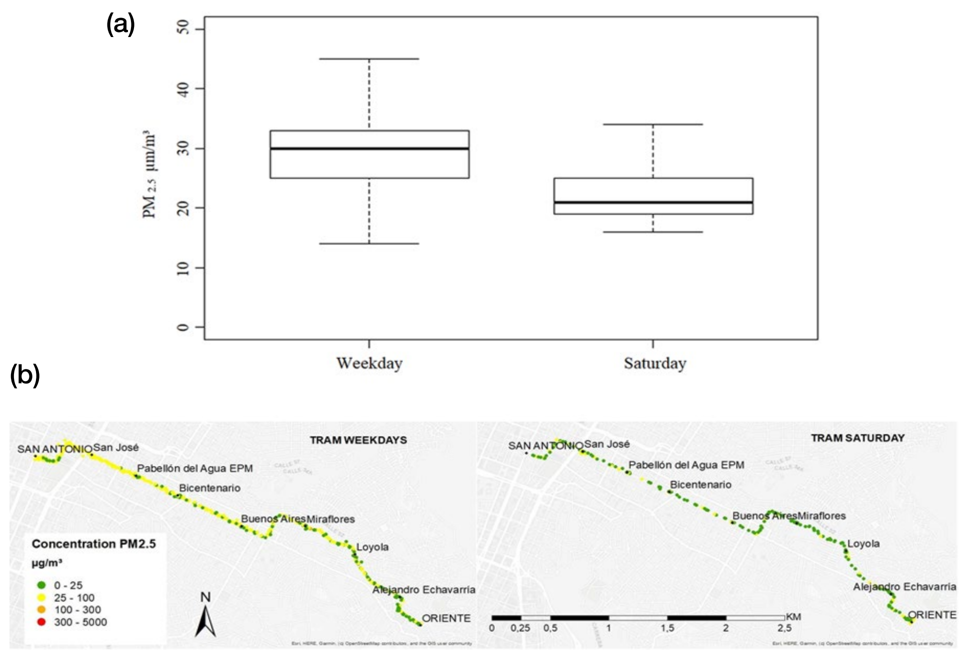

Fig. 4. Weekdays and Saturday Tram scenario (a) $PM_{2.5}$ concentrations (b) Spatial representation of concentrations.

2016). This effect is observed in Fig. 4.

The average and maximum $PM_{2.5}$ values are higher on weekdays ($PM_{2.5}$ average: 30 μg/m^3) than on Saturday ($PM_{2.5}$ average: 23 μg/m^3). This low concentration can be remarkable because of the exclusive lane of the tramcar that has interaction only with pedestrian paths. In this case, the Saturday concentration is within the OMS limit for $PM_{2.5}$ exposure.

3.4.3 Pilot Test Implementation TM Euro V B

The route chosen to monitor the implementation of a new fleet with Euro V technology in TM was the B-G-12, which runs through the system from the Portal Norte to the Portal Sur. The buses that operate this route are bi-articulated, which means they are part of Phase III and until 2018 they were mostly Euro IV technology. In 2019, Euro V buses were implemented as a pilot test to the B-G-12 route. The data found show no significant difference in the exposure to $PM_{2.5}$ with respect to the other technologies, since the old fleet had an average concentration of 116 μg/m^3 and the new fleet of 106 μg/m^3 (Fig. 5).

Euro IV technology or lower refers to vehicle fuel emission standards periodically established (generally

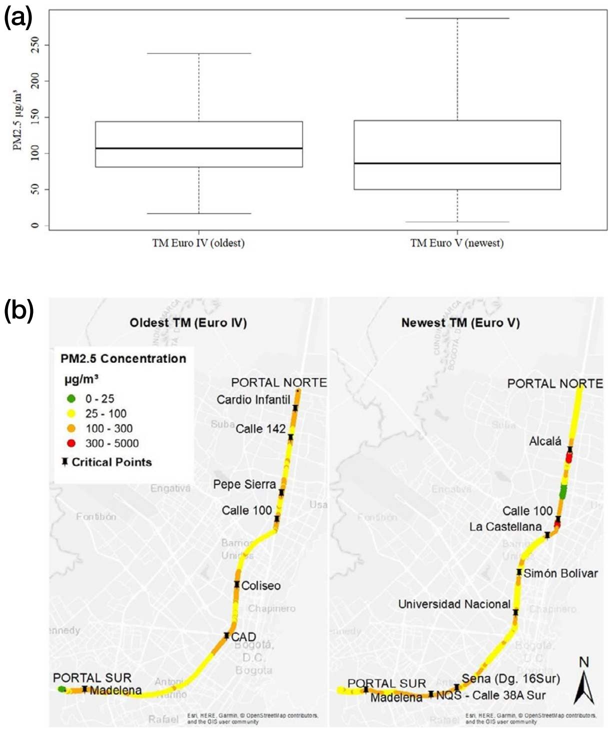

Fig. 5. TM Euro V new fleet scenario: (a) $PM_{2.5}$ concentrations graph and (b) $PM_{2.5}$ concentrations in the route.

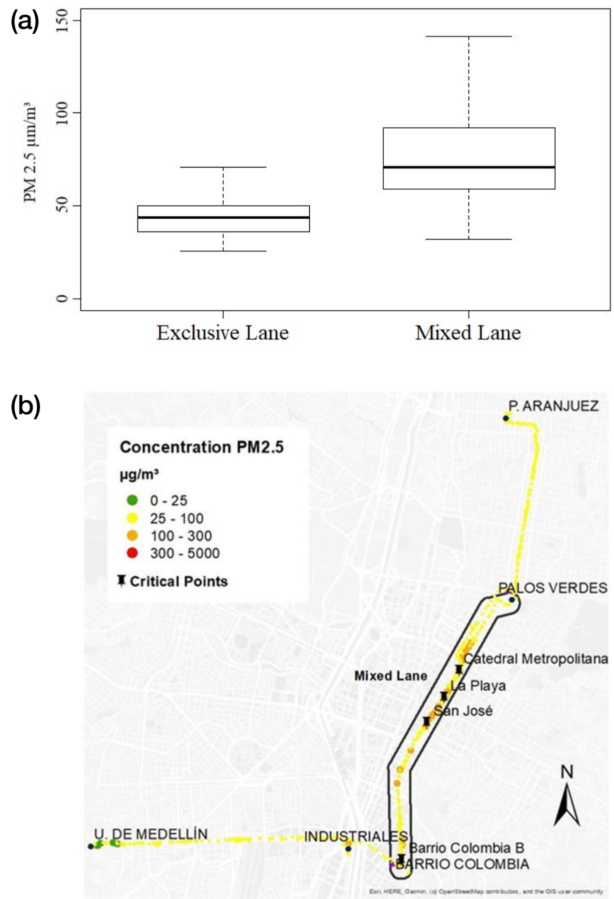

Fig. 6. Scenario of $PM_{2.5}$ concentrations in the mixed and exclusive lanes of BRT Line 2 of SITVA: (a) $PM_{2.5}$ concentrations and (b) $PM_{2.5}$ concentrations in the route. The boxed path refers to the mixed lane.

every 4 or 5 years) by the European Union before 2005. Euro V technology, declared in 2009, was established to reduce emissions of $PM_{2.5}$ in 5 times, compared with the immediately previous technology. The fleet of old vehicles measured is Euro IV technology. However, Fig. 5 evidences that the distribution of $PM_{2.5}$ is very similar in both scenarios, presenting almost the same critical areas along the way, where high concentrations are related to self-contamination but in addition to contributions from nearby external emissions.

It is noted that the interior of the buses measured for this analysis represents a microenvironment of prevailing concentrations between 25 µg/m³ and 100 µg/m³ and some exceedances of 300 µg/m³ of $PM_{2.5}$. When compared with Calle 80 and Caracas trunklines, belonging to Phase I with technology buses below Euro III, this microenvironment demonstrates a less risky scenario. Even so, the average exposure in both Euro IV and Euro V technologies exceeds more than 4 times the WHO standard for 24 hours.

With the implementation of Euro V technology, the system would expect to present a more favorable outlook with lower $PM_{2.5}$ exposure values, due to the emission standards for this pollutant with this technology. However, as Guevara (2018) stated, almost 80% of the concentration contributions come from nearby sources, thus, although there is a minimal reduction in $PM_{2.5}$ exposure in the new fleet with respect to the old one, the low proportion of Euro V vehicles operating in this trunkline has no effect of a decrease in exposure, since there is a greater presence of old technology vehicles in this trunkline.

3 .4. 4 Mixed Lane Impact on Line 2 BRT SITVA

The scenario observed when monitoring the BRT bus line 2 shows variations that are evident in the three segments indicated in Fig. 6, where the boxed path indicates the mixed lane. The first trip from the Universidad de Medellín is in the exclusive BRT bus lane and then it is integrated into a mixed lane to cover the demand for transport through the central corridor of the city. The distribution of data in the exclusive lane has concentrations with a much smaller range compared with the data for the mixed lane. The reduction of the average concentration of $PM_{2.5}$ (Table 8) of the exclusive lane with respect to the mixed one was of 45% and the dose reduction of 46%.

During the first journey in the exclusive lane from the Universidad de Medellín, the exclusive route of the gas BRTs is separated from the transit route of private vehicles and other types of transport mostly fueled by gasoline, which generate a smaller contribution of $PM_{2.5}$ than vehicles that use diesel. When BRT buses enter to the mixed lane from Barrio Colombia station to Palos Verdes, there is an increase in the average concentration of 80 $\mu g/m^3$, exceeding the average of the exclusive lane by 36 $\mu g/m^3$. The reason is that this lane travels through the center of the city along the Oriental Avenue, where (i) higher buildings are located; (ii) there are passenger transport vehicles with a greater contribution of $PM_{2.5}$ as they operate with diesel; and (iii) traffic increases as it is a highly busy main avenue where vehicles have acceleration and braking periods constantly under a low average speed that favors the emission of high concentrations of $PM_{2.5}$ (Guevara, 2018).

4. CONCLUSIONS

$PM_{2.5}$ personal exposure was evaluated in the massive public transport system of Bogotá (representative trunk lines of TM) and Medellín (all SITVA). Measuring campaigns were performed by continuous monitoring of $PM_{2.5}$ concentrations in the chosen journeys, considering the differences between vehicle technologies, infrastructure system and surrounding road structure.

Results show that TM, with diesel powered BRT and most of its vehicles with technologies inferior to EURO IV, has a personal exposure 5 times higher than the SITVA. The main reasons are attributed to the particular structure and characteristics of each system, as the SITVA is an electric powered system and some of its vehicles have GNC motors.

Likewise, the almost isolated microenvironments of SITVA electric vehicles create lower risk environments regarding dose and personal exposure to $PM_{2.5}$ emissions, also due to the low exchange of air with the external sources. Despite the tramcar system is at ground level, it has the lowest personal exposure because its surrounding areas are pedestrian paths.

TM is characterized for being composed of heavy diesel-powered vehicles. Due to this technology, the system produces high $PM_{2.5}$ emissions, additionally to its trunkline structure and vehicles with open system. All these factors favors the high personal exposure because of the exchange of polluted air from close emissions sources (mostly the same buses of the TM system) and the self-pollution process. Besides, the semi-closed structure of trunklines such as Caracas and Calle 80, specifically, makes difficult ventilation and dispersion process, hence these trunk lines had the highest personal exposure zones.

Meteorology and the time of year can play an important role in the levels of personal exposure to pollution within vehicles (Nazelle *et al.*, 2017). In times with high levels of urban pollution in cities, higher levels of personal exposure can occur within vehicles. This study did not consider the impact of meteorology or seasonality on the results. For future studies, it is recommended to carry out monitoring at different times of the year to evaluate its impact on the results. Even so, the measurements were developed during dry days.

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