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Research Article

Passengers Exposure to $PM_{2.5}$ in Self-polluted BRT-Diesel Operated Transport System Microenvironments

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ABSTRACT BRT (Bus Rapid Transport) vehicles are a frequented microenvironment, it consists of exclusive lines for the transport of passengers in articulated buses. In many large cities of developing countries BRT vehicles are diesel operated buses emitting important amounts of $PM_{2.5}$, a pollutant related with many health affectations. Evidence of high exposure levels have been reported onboard BRT vehicles, but detailed analysis of self-pollutions has not been developed. In this research, measurements of $PM_{2.5}$ inside the BRT system of Bogota called TransMilenio were performed. Speed and location data were recorded in real-time. In-situ measurements were performed in 3 lines of the system: Av. El Dorado, Av. Caracas and Calle 80, in different seat locations inside the buses. $PM_{2.5}$ concentrations above 120 $\mu g/m^3$ were measured for all the cases studied. Values above the 24 h WHO (World Health Organization) recommendation were registered. Trips were determined to be between 20 to 40 minutes per passenger. A CFD (Computational Fluid Dynamics) model was implemented to simulate the exhaust emissions from the buses, 3 traffic velocities of BRT were evaluated: 20, 32 and 60 km/h. Measurements and simulation results were used to calculate the self-pollution ratios inside the vehicles. The rear of the buses was identified as the most polluted section onboard with a ratio of self-pollution about 35% average.

KEY WORDS Microscale air quality, Particulate matter, Public transport, Diesel operated bus, Pollutant dispersion, Urban microenvironment

1. INTRODUCTION

Public transportation vehicles are frequented by the citizens making these microenvironments one of the places with most personal exposure of its users to pollution. One cost effective alternative in public transportation systems is the Bus Rapid Transit (BRT), these systems have large passenger capacity (more than 200 passengers per vehicle), fast travel speeds and short travel times since it has exclusive roadway, among other advantages (BRT Data Organization, 2019; Institute for Transportation and Development Policy, 2018; Piccirilo, 2012; ITDP *et al.*, 2010; Hidalgo and Graftieaux, 2008; Darido and Cain, 2007; Satiennam and Fukuda, 2006; Wright, 2005). However, recently BRT systems show disadvantages related with operative issues and pollutant emissions.

Many large cities around the world have BRT systems for passengers transportation, in the city of Bogota-Colombia, the main public transport system called TransMilenio (TM) is a large-scale BRT system. TM started its operation in December 1999. TM buses are articulated, and diesel operated, and has 113 km of dedicated lines distributed in 11 corridors, 134 stations and 9 terminals called "portals". It meets 30% of the transit demand in Bogota, transporting around 2.5 million passengers per day. TM fleet has been operating during more than 20 years and started to be systematically renewed in July 2019 (Cain *et al.*, 2013).

Particulate Matter of 2.5 microns particle diameter ($PM_{2.5}$) is directly related with cardiopulmonary disease and lung cancer and it is emitted from the diesel combustion of engines (Wyzga and Rohr, 2015). The effects of this pollutant are critical in sensitive populations such as children, elders and pregnant women. In large cities of developing countries, the BRT vehicles are diesel operated buses emitting important amounts of $PM_{2.5}$ with the potential of cause affectations to user's health. Evidence of high exposure levels have been reported onboard BRT vehicles (Morales *et al.*, 2019, 2017), but detailed analysis of self-pollution has not been developed. The analysis of this pollutant inside public transport buses is important to evaluate the consequences of vehicle emissions in public health, decision making about transportation technologies for a better urban infrastructure planning and future urban development (Arphorn *et al.*, 2018; Morales *et al.*, 2017; Adams *et al.*, 2015; Wyzga and Rohr, 2015; World Health Organization, 2006).

Personal exposure monitoring is an approach to evaluate the air pollution and public health issues, this approach allows to determine the dose directly received by a person from polluted air under various conditions (Morales *et al.*, 2019; Hern *et al.*, 2018; Strasser *et al.*, 2018). Previous studies have determined the personal dose to $PM_{2.5}$, ultra-fine particles and black carbon inside passengers of different transportation vehicle types: subway system, public buses, BRT, motorbikes, bicycle and private vehicle (Morales *et al.*, 2019; Hern *et al.*, 2018; Kumar *et al.*, 2018; Strasser *et al.*, 2018; Ham *et al.*, 2017; Xu and Hao, 2017; Karanasiou *et al.*, 2014).

The aim of this research is to use observed and simulated data to analyze spatially and temporally the passengers exposure to particulate $PM_{2.5}$ in TM, and quantify the ratios of self-pollution inside the BRT diesel operated vehicles (Institute for Transportation and Development Policy, 2018; Observatorio Ambiental de Bogota, 2017; Hidalgo *et al.*, 2013; Dario & Graftieaux, 2008).

Observed data consist of measurements in 3 of the main TM lines: Av. El Dorado, Calle 80 and Av. Caracas. Traffic velocity, location and $PM_{2.5}$ concentrations were measured in different seat locations. The Computational Fluid Dynamics (CFD) ANSYS Fluent® V 19 model was implemented to simulate $PM_{2.5}$ dispersion inside and outside the TM buses. The observed data and simulation results were used to quantify the self-pollution ratios at different TM traffic conditions. This approach allowed to estimate the impact of bus traffic velocity on $PM_{2.5}$ concentration at different locations, and to determine the places inside the bus with the highest concentrations of $PM_{2.5}$. This CFD approach has been previously implemented and validated to reproduce emissions of a traces gas experiment in urban buses (Guevara *et al.*, 2019; Li *et al.*, 2015; Behrentz *et al.*, 2004).

2. MATERIALS AND METHODS

The use of CFD coupled with measured data to study the in-cabin pollution dispersion in urban buses has been recently implemented and validated for different cases (Guevara *et al.*, 2019). This research was developed using ANSYS Fluent® V 19.

For CFD modeling and simulations, a server with 12 core intel Xeon processor, 16 Gb of RAM and an ATI Firepro video card was used.

This research consisted of two main stages: A measurement campaign on board the TM buses to record the observed data, and the CFD modeling of the pollutant dispersion to obtain the exposure maps and TM self-pollution ratios.

2. 1 Measuring Campaign (observed data)

The massive transport system of Bogota-Colombia consists of different lines, for the measuring campaign 3 of the most important were selected: Calle 80, Av. Caracas and Av. El Dorado, considering information such as passenger demand, bus emission technology, rush hours and environment characteristics (buildings, vegetation, etc). For the development of the measurement campaign in-situ data was recorded for the TM buses on the defined 3 lines. A TSI DustTrak II 8530 was used to get real-time data of the $PM_{2.5}$ in-cabin concentration of the TM, alongside with the optical instrument a calibration

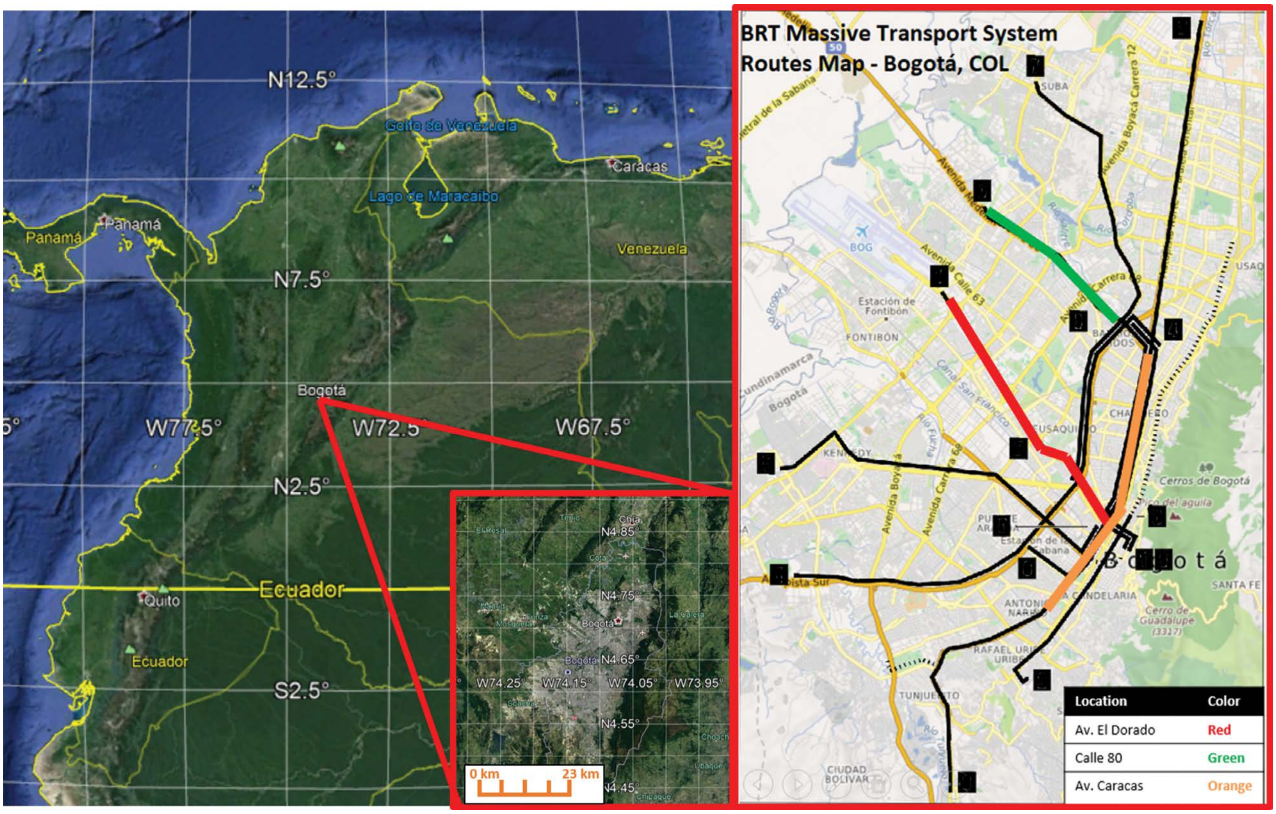

Fig. 1. TransMilenio (TM) public transportation system Lines in the measuring campaign.

measurement with PEMs (Personal Exposure Monitoring) was developed simultaneously to validate the optimal instrument data recorded. The measurement of the $PM_{2.5}$ concentration was coupled with GPS. The location data regarding latitude, longitude, altitude and speed during the travels performed in the system was recorded.

The massive transport system covers 70% of the city and the selected lines are around a 40% of the whole actual system. Fig. 1 shows the 3 main lines: Av. El Dorado, Calle 80 and Av. Caracas. In these lines, the measurement campaign was developed on board TM routes, all the trips were aboard buses with technology EURO II emission standard.

Measurement campaign consisted of 30 hours of in-situ monitoring on board of the buses, distributed in the 3 mentioned lines, and in different position seats inside the bus cabin. First measures were taken during December of 2017, and the rest during April and May of 2018. Measurements were performed from 12:00 to 19:00. These are off peak hours with a reduced number of passengers, these periods were selected to avoid the impact of passengers with measurements and CFD modeling. Detailed data of the measuring campaign is presented in the Table 1.

2.2 CFD Modeling

2.2.1 Geometry

To evaluate the self-pollution fraction of the in-cabin a CFD model was developed. This model was performed for an articulated bus of TM. The geometrical and operating parameters were taken from a datasheet of the EURO II articulated bus model (BRT Data Organization, 2019).

A tridimensional geometry of the TM bus was built (Fig. 2), the main features of the bus were considered in detail such as windows location and dimension, bus exhaust location, doors and passages. 2 main simplifications were made: The bus was simulated without passengers inside, and passenger seats were not included in the simulations. The Fig. 1 shows the geometry obtained from this construction.

CFD modeling is based in the solution of Navier-Stokes and transport phenomena equations in a discretized

Table 1. Measuring campaign information for the 3 public transportation lines: Av. El Dorado, Calle 80 and Av. Caracas.

Line	Av. El Dorado	Calle 80	Av. Caracas
Date	18/12/2017; 19/12/2017; 23/05/2018; 24/05/2018	30/05/2018	25/05/2018; 26/05/2018
Hours measured	16	6	8
TM Vehicle Emission Standard	EURO II	EURO II	EURO II
Hour	13:30 to 19:00	14:30 to 19:00	13:30 to 18:00

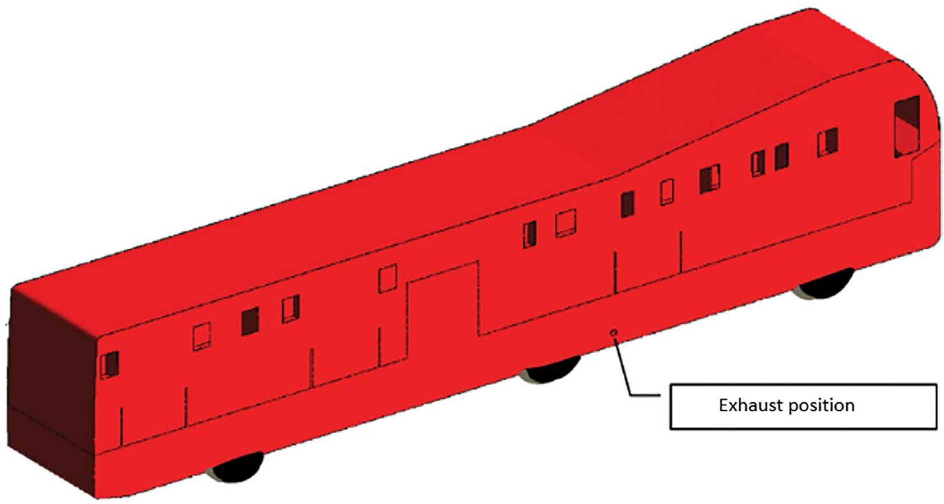

Fig. 2. Geometry of the articulated Bus Rapid Transit (BRT) built for the CFD (Computational Fluid Dynamics) modeling of $PM_{2.5}$ dispersion and self-pollution.

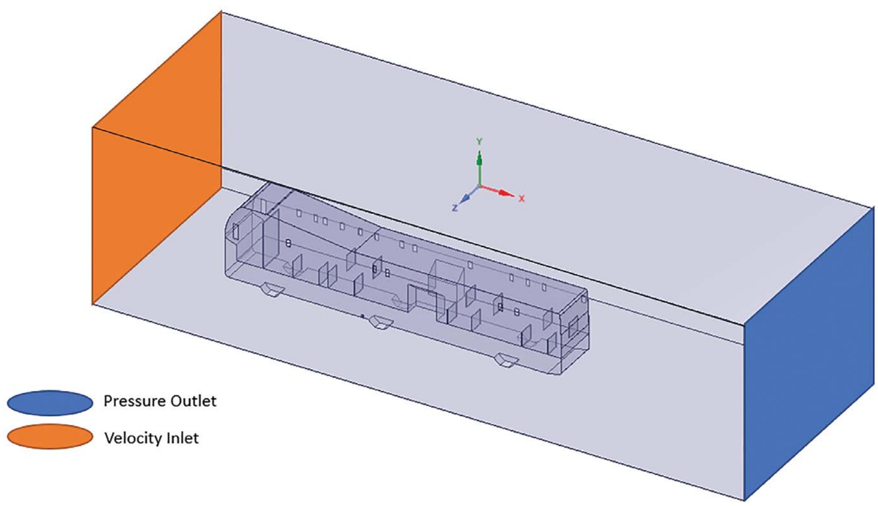

Fig. 3. CFD modeling domain and boundary conditions for BRT vehicle simulation.

flow domain that considers the surrounding and internal air of the BRT. Hence the CFD model is solved in transitory state for an interval of time, the bus geometry is placed inside a box of dimensions $12 \times 9 \times 35$ meters (Fig. 3), this approach allows the flow to be fully developed during the simulation time, and is realistic and consistent with the shape of the road ways of the BRT public transportation system. The surfaces with colors are mass inlet and outlet boundaries, and the other surfaces are considered as walls with non-slide condition.

2.2.2 Mesh

The meshing for the system domain was developed using a non-structured approach. The mesh quality is one of critical aspects in the convergence of the simulation, for this reason, the meshing process must consider quality criteria that assures a high numerical reliability during the calculations. A high-quality mesh can be obtained through 2 possible ways: 1-mesh convergence analysis, or 2- Quality criteria analysis of mesh elements. In this study an element quality criterion for the meshing was implemented.

The Orthogonal Quality Criterion (OQC) was implemented, this criterion is based in the similarity between each element of the mesh and a perfect cube (OQC = 1). For bad quality elements the OQC will has a value close to 0, meanwhile a good quality element will have an OQC value close to 1. The OQC was used to assess the element quality by defining a minimum tolerable value of OQC = 0.005 for the worst element in the mesh. This hypothesis allows to ensure the worst element in the mesh, in terms of quality, will be good enough to avoid convergence issues caused by the mesh.

To perform the CFD modeling an initial non-structured mesh of tetrahedral elements (Fig. 4-a) was built, the obtained mesh is made of more than 14 million elements and with a minimum OQC of 0.206, which according to (reference) corresponds to a good quality mesh. This raw mesh has a good quality with an OQC over 0.005, but the large number of elements would be highly demanding in computational resources. For this reason, a conversion-optimization to polyhedral mesh was performed (Fig. 4-b) aiming to reduce the mesh size without losing mesh quality. With the mesh optimization a lower mesh size with 2.9 million of elements was achieved, and at the same time a good quality OQC with 0.117 was obtained. The initial and optimized mesh sizes and OQC are summarized in Table 2. The optimized polyhedral mesh was the input used for the CFD simulations performed.

2.2.3 Set-up

CFD modeling is based in the Navier-Stokes equations (Eqs. 1, 2, 3 and 4) numerical solution for a fluid system, it is also possible to consider with this approach the transport phenomena involved in the simulation. The Eq. 5 is the general transport equation in its differential formulation for any variable transport variable (φ). For this case turbulence variables and pollutant composition

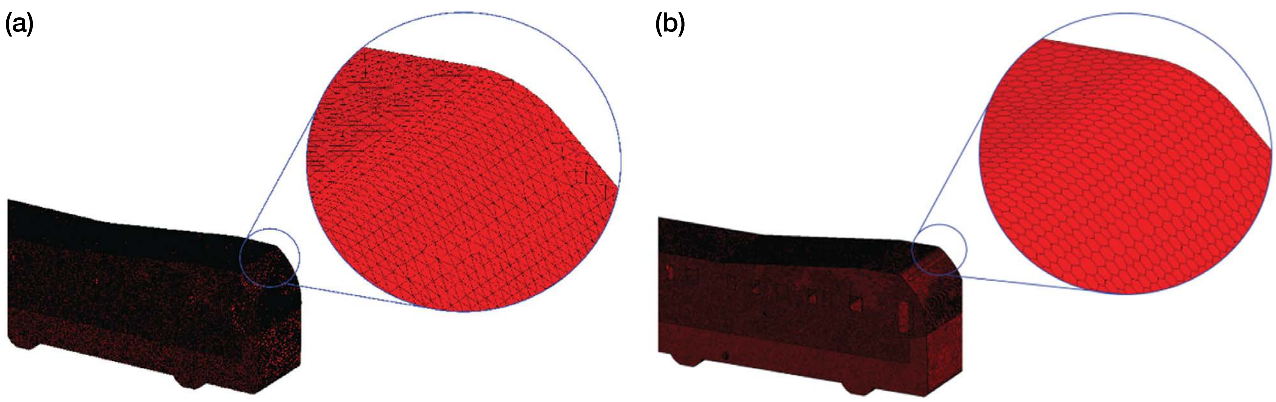

Fig. 4. Tetrahedral (a) and polyhedral (b) meshes for the CFD modeling of the BRT vehicles.

Table 2. Mesh size and quality for the CFD modeling of the BRT vehicle.

Tetrahedral mesh		Polyhedral mesh	
Number of elements	14,025.910	Number of elements	2,915.668
Minimum orthogonal quality	0.206	Minimum orthogonal quality	0.117
Maximum orthogonal quality	0.992	Maximum orthogonal quality	0.882

are variables to be considered inside the model.

Momentum:

$$\frac{\partial}{\partial t}(\rho\vec{V}) + \nabla\cdot(\rho\vec{V}\vec{V}) = -\nabla P + \nabla\cdot(\tau) + \rho\vec{g} + \vec{F} \qquad \text{Eq. 1}$$

$$\text{Continuity: } \frac{\partial\rho}{\partial t} + \frac{\partial}{\partial t}(\rho\vec{V}) = S_m \qquad \text{Eq. 2}$$

$$\text{Energy: } \frac{\partial}{\partial t}(\rho E) + \nabla\cdot\left(\vec{V}(\rho E + P)\right)$$

$$= \nabla\cdot\left(K_{eff}\nabla T - \sum_j h_j J_j + \tau_{eff}\vec{V}\right) + S_h \qquad \text{Eq. 3}$$

$$\vec{V} = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\right) \qquad \text{Eq. 4}$$

$$\underbrace{\frac{\partial}{\partial t}(\rho\varphi)}_{\text{Transitory term}} + \underbrace{(\nabla\cdot(\rho\vec{V}\varphi)}_{\text{Convective term}} = \underbrace{\nabla\cdot(\Gamma\nabla\varphi)}_{\text{Diffusive term}} + \underbrace{S_h}_{\text{Source term}} \qquad \text{Eq. 5}$$

The CFD model set-up used is a transient formulation solver. The system turbulence was modeled using the k-epsilon realizable model (Eqs. 6, 7 and 8) with the parameters described in Table 3.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho\bar{u}_i k)$$

$$= P_k + P_b - Y_M - \rho\varepsilon + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + S_k \qquad \text{Eq. 6}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\bar{u}_i\varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right] + \rho C_1 S_\epsilon$$

$$-\rho C_2\left(\frac{\epsilon^2}{k + \sqrt{\nu\epsilon}}\right) + C_1\frac{\epsilon}{k}C_3 P_b + S_\epsilon \qquad \text{Eq. 7}$$

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right],\ \eta = S\frac{k}{\epsilon},\ S = 2\sqrt{2S_{ij}S_{ij}},$$

$$\mu_t = \rho C_\mu\frac{k^2}{\epsilon} \qquad \text{Eq. 8}$$

Table 3. K-epsilon turbulence modeling parameters used for CFD modeling.

Parameter	Value
C_1	1.44
C_2	1.92
σ_k	0.85
σ_ε	0.85
C_μ	0.09
Turbulent Schmidt	0.7

In equations 6 to 8, P_K represents the generation of turbulence kinetic energy due to mean velocity gradients, calculated in the same way as standard k-epsilon model. P_b is the generation of turbulence kinetic energy due to buoyancy effects, calculated in the same way as standard k-epsilon model. Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate (Versteeg and Malalasekera, 1995; CHIEN, 1982; NASA-Langley Research Center, n. d.).

The k-epsilon turbulence model was selected since it has a good performance in terms of computational resources and simulation time with accurate results. To select this turbulent modeling approach other important features of the k-epsilon realizable turbulence model were considered: 1- Turbulent Energy Dissipation rate (ε) is derived from the square mean of vorticity, 2- Predicts with precision the split velocity in propulsion systems or injection jet in plane and curve geometries, and 3- Higher reliability than k-epsilon standard when flows with high pressure gradients, swirl flows and splits and recirculation (Zapata *et al.*, 2018; Versteeg and Malalasekera, 1995).

The pollution concentration and dispersion were modeled using the Species to Transport model. This model is based in a Multicomponent-Single-Phase-Eulerian approach. The numerical formulation is based in the general transport equation (Eq. 5) with the pollutant concentration (x) as transport variable instead of φ. The multicomponent system is them composed by: Air as N_2 and O_2 and $PM_{2.5}$.

The under-relaxation factors used for the CFD modeling of the BRT are shown in Table 5. Fig. 3 shows the boundary conditions and location, the grey surfaces are walls including bus surface, and inlet and outlet mass boundary conditions in orange and blue colors. respectively. The position of the bus exhaust is shown in Fig. 2. The $PM_{2.5}$ emission factor at the average bus travel

Table 4. Methods used in the CFD modeling set-up.

Pressure-Velocity coupling	SIMPLE scheme
Gradient	Least squared cells based
Pressure	Second order
Momentum	Second order upwind
Turbulent kinetic energy	First order upwind
Turbulent dissipation rate	First order upwind
$PM_{2.5}$ concentration	Second order upwind
O_2 concentration	Second order upwind
Energy	Second order upwind
Transient formulation	First order implicit

speed is taken from the Bogota's emission inventory $(2.29 \times 10^{-6} \frac{kg_{PM_{2.5}}}{s}$ at 28 km/h) (Arphorn *et al.*, 2018).

The convergence criteria used was the residual absolute values of 0.001 for the equation of the numeric system involved: continuity, momentum x, y and z, energy, k, epsilon, $PM_{2.5}$ and O_2 concentration.

3. RESULTS AND DISCUSSION

3.1 $PM_{2.5}$ Concentration in the Cabin

Data recorded during the measuring campaign for the instantaneous position was used to calculate the instantaneous velocity and acceleration of the vehicles in the lines. The results for the velocities and acceleration of the articulated BRT in the 3 lines (Av. Caracas, Calle 80 and Av. El Dorado) are presented in Fig. 5. Most of the travel bus velocities are between 30 and 45 km/h, about 30% of the data collected is in this range.

Table 5. Under-relaxation factors of variables used in CFD modeling.

Parameter	Value
Pressure	0.3
Density	1.0
Body forces	1.0
Momentum	0.7
Turbulent kinetic energy	0.8
Turbulent dissipation rate	0.8
Turbulent viscosity	1.0
$PM_{2.5}$	1.0
O_2	1.0
Energy	1.0
Time step value constant	0.02 s

From Fig. 5 the data collected corresponding to velocities of 0 m/s is about 8%. 3% of the data has acceleration (and deacceleration) values of 0 m/s^2. This leads to consider the vehicle is almost always moving with an acceleration value different to 0 m/s^2. This observation is evidence of a highly dynamic behavior of the bus transit in the city since the acceleration values different to 0 m/s^2 means the velocity is not constant but for a few moments. These observations are evidence of an unstable traffic conditions for the TM system in the city.

The most frequent traffic velocity values observed are: 10 to 30 km/h, 30 to 45 km/h and 0 to 10 km/h. These observations were used to define the traffic velocity values for the CFD simulations (20, 36 and 60 km/h).

Fig. 6 shows the distribution of the variables: pollutant $PM_{2.5}$ concentration, traffic velocity and acceleration, at the 3 lines of TM. The distribution is based on the traffic velocity and acceleration intervals shown in the Fig. 6. The values showed in the top of the vertical bars are the maximum values of $PM_{2.5}$ concentration for a traffic condition of the bus (acceleration or velocity).

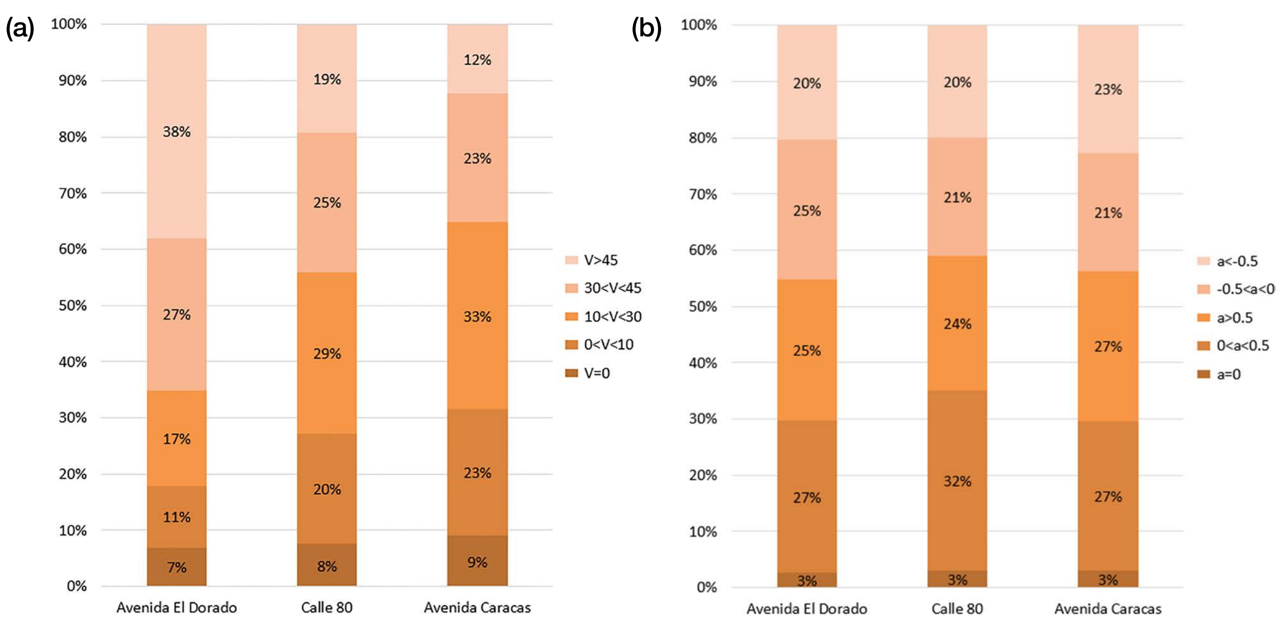

Fig. 5. Traffic variables distribution of BRT vehicles: (a) velocity (km/h), (b) acceleration/deacceleration (m/s^2).

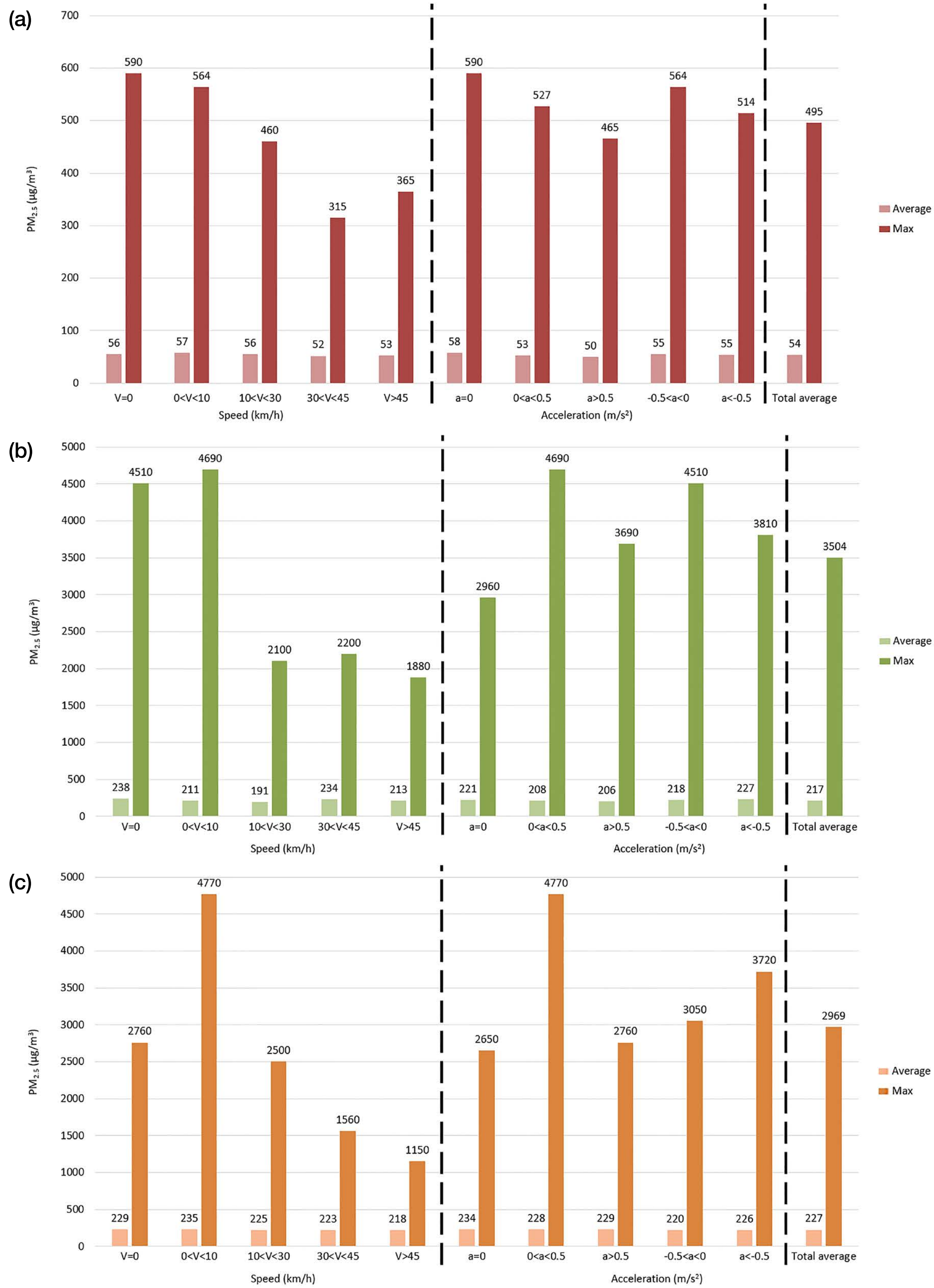

Fig. 6. $PM_{2.5}$ concentration ($\mu g/m^3$) distribution according to BRT traffic velocity (km/h) and acceleration (m/s^2): (a)Av. El Dorado, (b) Calle 80 and (c) Av. Caracas.

From the measured data was identified the line Calle 80 is the most polluted in terms of average $PM_{2.5}$ concentrations. Av. El Dorado is the line with the least polluted buses.

From Fig. 6 was stablished the velocity and acceleration intervals in which the passengers are more exposed to $PM_{2.5}$ during their trips. According to the data recorded high exposure levels are presented at low velocities and acceleration conditions (velocity between 0 and 10 km/h, acceleration between 0 and 0.5 m/s^2) reaching peak values of more than 4000 $\mu g/m^3$ in the lines of Calle 80 and Av. Caracas. And more than 50 $\mu g/m^3$ in Av. El Dorado.

The $PM_{2.5}$ concentration reached average values of 220–240 $\mu g/m^3$ in the lines of Calle 80 and Av. Caracas. And more than 35 $\mu g/m^3$ in Av. El Dorado. Even so, the average values al almost invariant with the traffic conditions, this means the average pollution levels at different acceleration and velocity values in the same line are almost the same.

In Fig. 7 the concentration of $PM_{2.5}$ relationship with the velocity along the trip time can be observed. Other way to analyze the plotted data is use it as evidence of the relationship between the conduction cycle and the in-cabin pollution in terms of $PM_{2.5}$ concentration. This information is shown for the 3 representative trips on the TM lines.

From the data collected (Fig. 7) is possible to extract the background concentration of $PM_{2.5}$ in the 3 lines: 20, 25 and 50 $\mu g/m^3$ for Av. El Dorado, Calle 80 and Av. Caracas, respectively. The peaks above this value are high exposition hot-spots due to self-pollution.

In Fig. 7 the last minutes plotted in the time series corresponds to BRT traffic in the terminals (portales), located at the beginning and ending of the trips. For the line of Av. Caracas, the highest value of $PM_{2.5}$ concentration

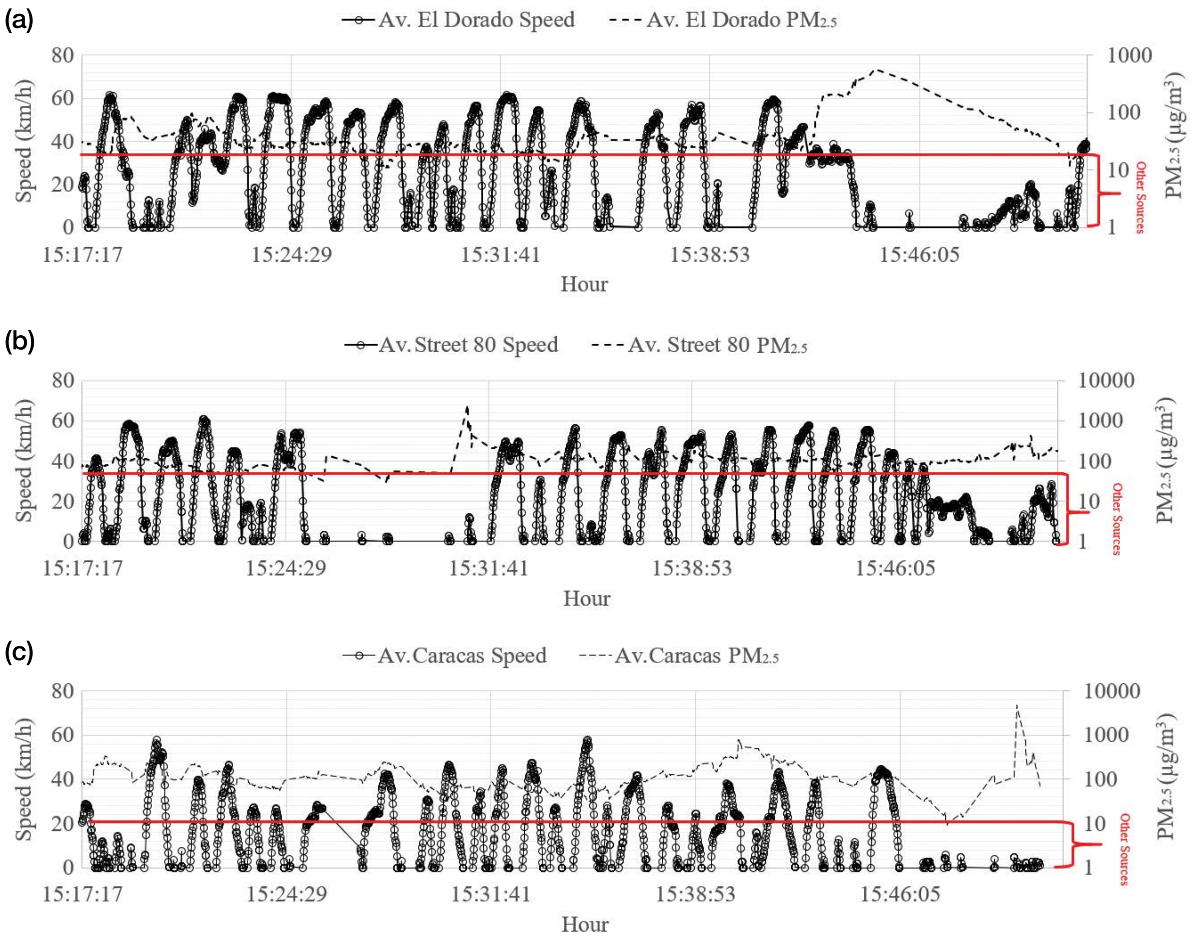

Fig. 7. Measuring campaign results of speed (km/h) and $PM_{2.5}$ concentration ($\mu g/m^3$) measured at: (a) Av. El Dorado, (b) Calle 80 and (c) Av. Caracas.

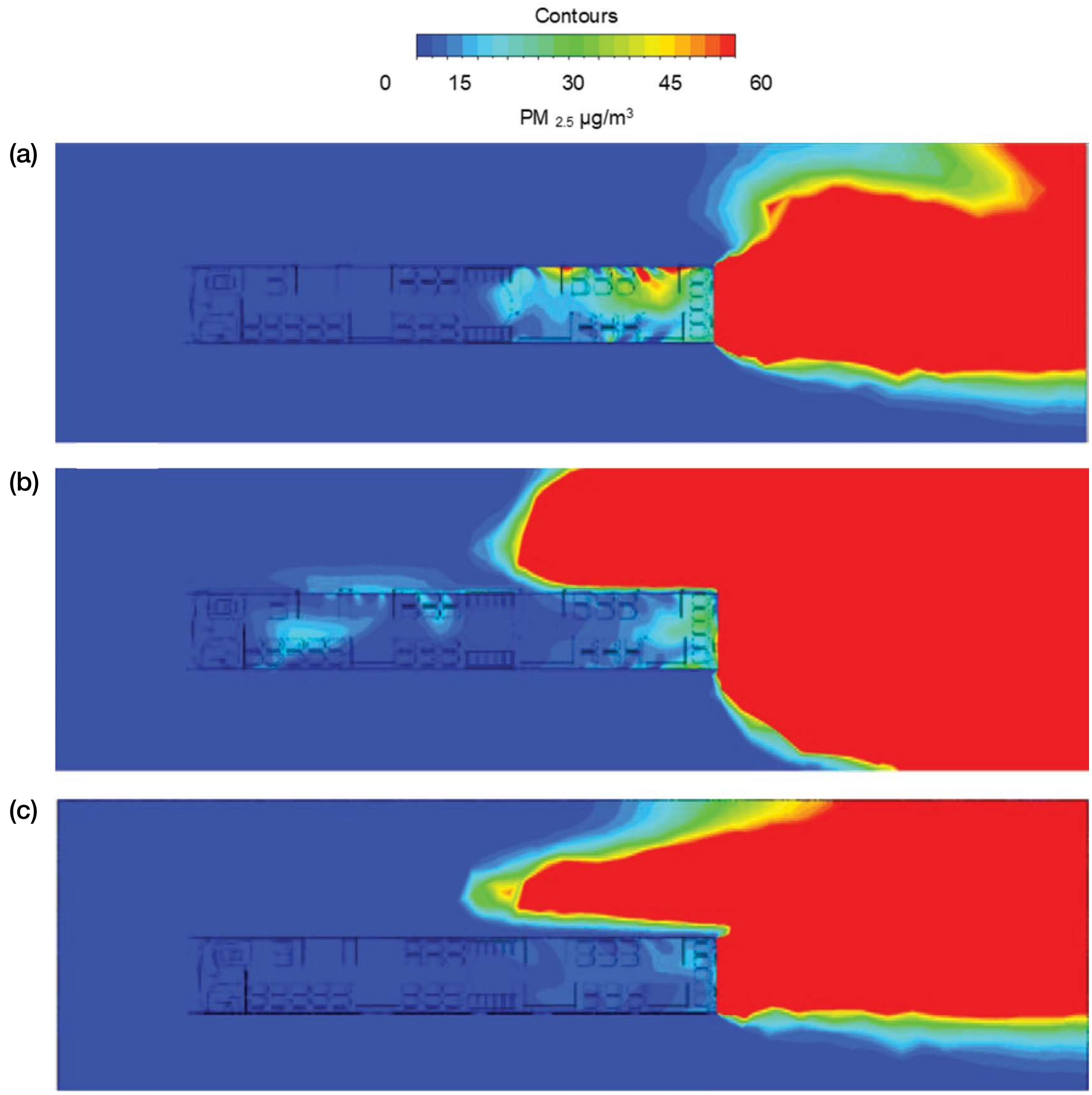

Fig. 8. Pollution contour maps of $PM_{2.5}$ concentration (μg/m^3) outside the BRT at traffic velocity of: (a) 20 km/h, (b) 36 km/h and (c) 60 km/h.

can be observed at the last point evidencing the pollution exposure of all the passengers, and non-passengers, located in the roadways and platforms in the last stop of the route.

To validate our results, we compared our measurements with results reported by previous measurement campaigns in Bogota (Morales *et al.*, 2019, 2017). The $PM_{2.5}$ mean value reported in these previews studies (177 μg/m^3) is in the same range of the values observed in the results obtained from this campaign (54 μg/m^3 in Avenida El Dorado, 217 μg/m^3 in Calle 80 and 227 μg/m^3 in Avenida Caracas). Our measurements also show the same trends reported by other authors.

3.2 CFD Simulations

To establish the ratio of self-pollution in the BRT vehicles the data collected from the measuring campaign was complemented with CFD modeling results. This approach leaded to the detailed $PM_{2.5}$ concentration distribution inside and outside the BRT vehicle (Figs. 8 and 9) in a near-real traffic conditions. The obtained results were used to calculate the self-pollution fraction at 3 TM traffic condition (20, 36 and 60 km/h) (Fig. 9 and Table 6).

From the CFD results was observed that the plume of

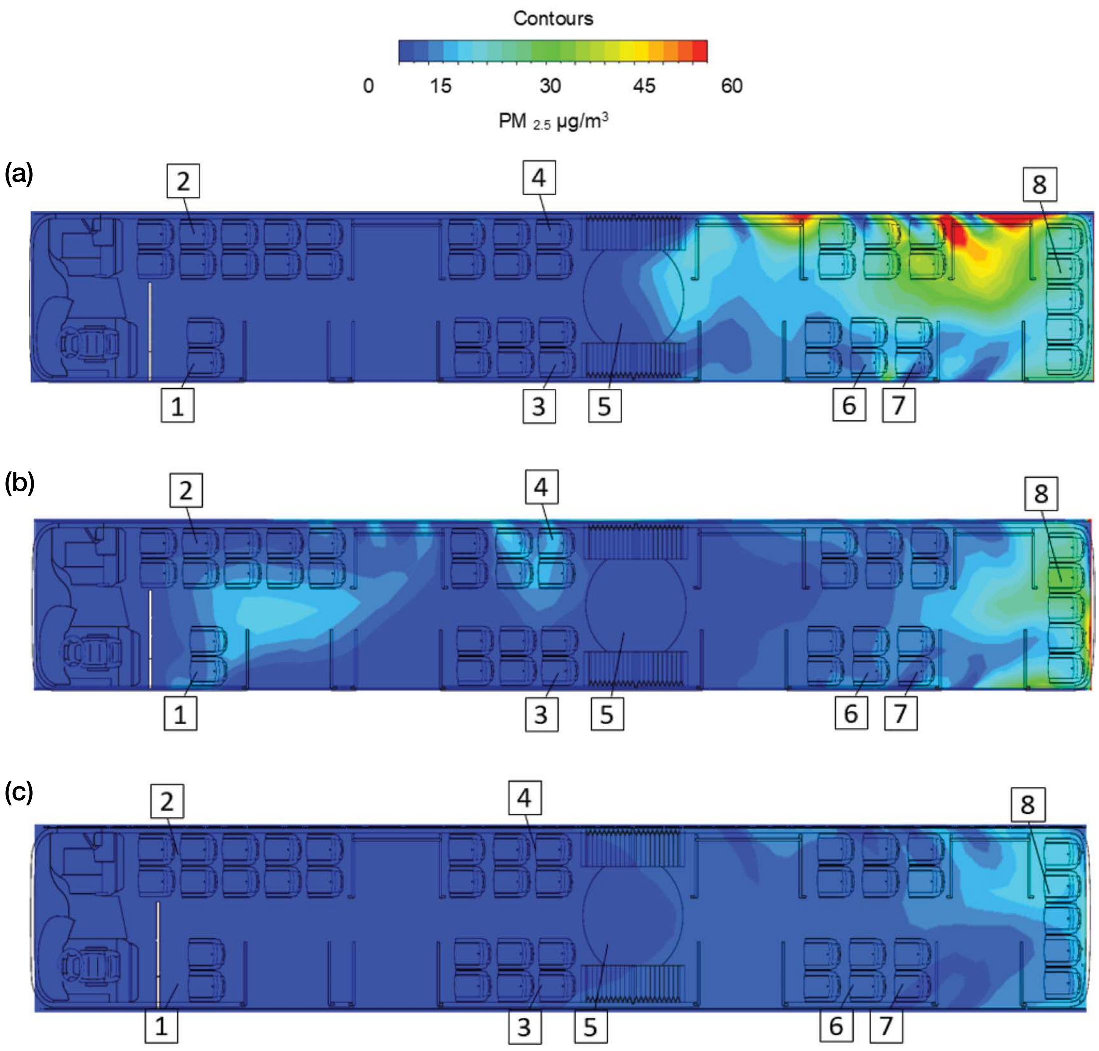

Fig. 9. Self pollution contour maps of $PM_{2.5}$ concentration ($\mu g/m^3$) and measuring positions inside the BRT at traffic velocity of: (a) 20 km/h, (b) 36 km/h and (c) 60 km/h.

gases emitted from the exhaust are dispersed mainly outside back to the vehicle, and mainly to the right side of the BRT (Fig. 8). This dispersion pattern evidences an important affectation to other vehicles and non-TM passengers, mainly to motorcycles, making the passengers of that type of small vehicle to be exposed to pollution emitted from TM. This situation has been evidenced before in the data reported in previews studies in Bogotá (Morales *et al.*, 2019, 2017).

Self-pollution phenomenon was analyzed based on simulated and observed results at different traffic velocities, the 3 simulated cases showed a similar pattern of pollution distribution and ventilation inside the BRT vehicles. The pollution emitted from the exhaust of the BRT vehicles trends to concentrates at the rear part of the inner cabin, location 8 in the Fig. 9 contour maps.

The concentration of the $PM_{2.5}$ inside the BRT vehicle cabin is higher at low velocities according to the simulation results (Fig. 9). These results are consistent with the observation data recorded from the measuring campaign (observed data). At the highest traffic velocity of 60 km/h the ventilation effect is stronger, making the self-pollution ratio smaller than at lower velocities (20 and 36 km/h).

By using the observed data, and from the simulation results of the implemented CFD model, the background $PM_{2.5}$ concentration and self-pollution ratios were calculated (Table 6). The results are summarized in terms of

Table 6. Self pollution ratio of $PM_{2.5}$ concentration (μg/m^3) inside the BRT at traffic conditions of 20 km/h, 36 km/h and 60 km/h.

Traffic velocity	Position	Mean concentration		Other sources	Self-pollution ratio
		$PM_{2.5}$ at 20 km/h (μg/m^3)	$PM_{2.5}$ simulated (μg/m^3)	$PM_{2.5}$ background (μg/m^3)	
20 km/h	1	19.9	0	19.9	0%
	2	41.2	0	41.2	0%
	3	27.2	0	27.2	0%
	4	69	0.1	68.9	0%
	5	41	3.6	37.4	9%
	6	77	12.6	64.4	16%
	7	59.3	21.2	38.1	36%
	8	59	40.7	18.3	69%
	Average	49.2	9.8	39.4	16%
36 km/h	1	23.3	2.4	20.9	10%
	2	21.4	2.1	19.3	10%
	3	22.5	0.1	22.4	0%
	4	27.5	7.8	19.7	28%
	5	35.8	1.4	34.4	4%
	6	38.4	6.9	31.5	18%
	7	63.9	7.1	56.8	11%
	8	56	35.2	20.8	63%
	Average	36.1	7.9	28.2	18%
60 km/h	1	18.4	1.3	15.0	8%
	2	45	1.2	17.2	7%
	3	23.5	2	21.5	9%
	4	66	2.2	24.4	8%
	5	32.3	2.6	29.7	8%
	6	16.3	4.7	40.3	10%
	7	65.2	5.7	60.3	9%
	8	26.6	15.5	49.7	24%
	Average	36.7	4.4	32.3	10%

$PM_{2.5}$ concentration measured, $PM_{2.5}$ concentration simulated (self-pollution), their difference (Background) and the self-pollution ratio for the BRT vehicle.

The self-pollution was calculated as the ratio between the $PM_{2.5}$ concentration simulated and observed, this ratio is reported as percentage. These quantitative results confirm the observations of $PM_{2.5}$ concentration hot-spots due to self-pollution in the rear part of the bus cabin.

The highest self-pollution ratios were found at low velocities in the rear part of the bus, with values of more than 60% at 20 and 36 km/h. In the case of the maximum traffic velocity (60 km/h) the highest self-pollution ratio obtained was 24% at the rear part of the bus cabin.

From simulation results the traffic velocity of 60 km/h is 12% of the traffic-time in the line of Av. Caracas, the most polluted line in the city. Calle 80 was identified as the second more polluted line; in Calle 80 the velocity of 60 km/h is the traffic condition 19% of the trip time. In the line of Av. El Dorado, 60 km/h TM vehicle velocity is 38% of the trip time.

Since the trips in the line of Av. El Dorado are more ventilated and less self-polluted, the trips on board the TM vehicles in this line are less harmful to human health, even when the mean values are still above the WHO recommendation (25 μg/m^3).

4. CONCLUSIONS

Passengers are being exposed to high concentrations of $PM_{2.5}$ ($PM_{2.5} > 100$ μg/m^3) during trajectories from 20 to 40 minutes in the TM diesel-based vehicles.

The data measured showed the most polluted line of the public transportation BRT system of Bogota (TM) is Av. Caracas, the second most polluted is the Calle 80 line and the third is the Av. El Dorado. Av. Caracas line was identified as segment of TM system with the most harmful conditions to travel as passenger.

Since the location of Av. Caracas line is at the City down-town, the obtained results evidenced higher pollution levels at the down-town urban area of the city. Based on that evidence, new projects of transportation infrastructure development, and urban planning must consider clean technologies for mobility solutions to avoid bigger public health affectations to citizens and TM users.

CFD modeling was implemented to accurately simulate the in-cabin pollution dispersion. The self-pollution ratios, $PM_{2.5}$ concentration dispersion and background concentrations were obtained for 3 different transit velocities of 20, 32 and 60 km/h. Simulation results and observations of $PM_{2.5}$ concentrations were processed to obtain data about the self-pollution in each in-cabin location at 3 different traffic velocities (20, 36 and 60 km/h) of TM system. Furthermore, Simulation results for TM showed hotspots of pollution and allowed to demonstrate that a fraction of $PM_{2.5}$ concentration measured inside the bus corresponds to self-pollution from exhaust emissions with values up to 69%.

The highest levels of self-pollution, with an average value of 35%, were identified in the rear part of the TM vehicles, showing these seat locations inside the TM buses are the most polluted due to the emissions from the TM vehicle exhaust.

Based on the simulated and observed data the line of Av. El Dorado was identified as the more ventilated, due to better traffic conditions, and less polluted background (Figs. 6 and 8), leading to a less harmful trip conditions for the TM passengers. Even so, the 3 lines analyzed present $PM_{2.5}$ concentration with higher levels than the WHO recommendation (25 $\mu g/m^3$).

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REFERENCES

Adams, K., Greenbaum, D.S., Shaikh, R., van Erp, A.M., Russell, A.G. (2015) Particulate matter components, sources, and health: Systematic approaches to testing effects. Journal Air Waste Management Association, 65, 544–558. https://doi.org/10.1080/10962247.2014.1001884

Arphorn, S., Ishimaru, T., Hara, K., Mahasandana, S. (2018) Considering the effects of ambient particulate matter on the lung function of motorcycle taxi drivers in Bangkok, Thailand. Journal Air Waste Management Association, 68, 139–145. https://doi.org/10.1080/10962247.2017.1359217

Behrentz, E., Fitz, D.R., Pankratz, D.V., Sabin, L.D., Colome, S.D., Fruin, S.A., Winer, A.M. (2004) Measuring self-pollution in school buses using a tracer gas technique. Atmospheric Environment, 38, 3735–3746. https://doi.org/10.1016/j.atmosenv.2004.04.007

BRT Data Organization (2019) Global BRT Data. https://brtdata.org/.

Cain, A., Darido, G., Baltes, M.R., Rodriguez, P., Barrios, J.C. (2013) Applicability of TransMilenio Bus Rapid Transit System of Bogotá, Colombia, to the United States. Center for Urban Transportation Research (CUTR), University of South Florida, 1, 86.

Chien, K.-Y. (1982) Predictions of channel and boundary-layer flows with a low-Reynolds-number two-equation model of turbulence. American Institute of Aeronautics and Astronautics, 20, 33–38. https://doi.org/10.2514/6.1980-134

Darido, G., Cain, A. (2007) Report on South American Bus Rapid Transit Field Visits: Tracking the Evolution of the TransMilenio Model, 1–40.

Guevara, F., Guevara, M., Belalcazar, L. (2019) CFD Modeling and Validation of Tracer Gas Dispersion to Evaluate Self-pollution in School Buses. Asian Journal of Atmospheric Environment, 13, 1–10. https://doi.org/10.5572/ajae.2019.13.1.001

Ham, W., Vijayan, A., Schulte, N., Herner, J.D. (2017) Commuter exposure to $PM_{2.5}$, BC, and UFP in six common transport microenvironments in Sacramento, California. Atmospheric Environment, 167, 335-345. https://doi.org/10.1016/j.atmosenv.2017.08.024

Hern, Y., Andraca-ayala, G.L., Id, U.D., Gochicoa-rangel, L., Rosas-p, I. (2018) Personal Exposure to $PM_{2.5}$ in the Megacity of Mexico: A Multi-Mode Transport Study. Atmosphere (Basel), 1-14. https://doi.org/10.3390/atmos9020057

Hidalgo, D., Graftieaux, P. (2008) Bus Rapid Transit Systems in Latin America and Asia: Results and Difficulties in 11 Cities. Transportation Research Record: Journal of the Transportation Research Board, 2072, 77-88. https://doi.org/10.3141/2072-09

Hidalgo, D., Pereira, L., Estupiñán, N., Jiménez, P.L. (2013) TransMilenio BRT system in Bogota, high performance and positive impact - Main results of an ex-post evaluation. Research in Transportation Economics, 1, 138.

Institute for Transportation and Development Policy, I. (2018) BRT Planning Guide: Environmental Performance. New York, USA.

ITDP, Arias, C., Castro, A., Martins, W.C., Custodio, P., Diaz, J.C., Fjellstrom, K., Hidalgo, D., Hook, W., King, M., Wei, L., Litman, T., Menckhoff, G., Midgley, P., Pardo, C., Sandoval, E.E., Szasz, P., Tiwari, G., Vlasak, J., Willmunsen, L., Wright, L., Zimmerman, S. (2010) Guía de Planificación de Sistemas BRT Autobuses de Tránsito Rápido 37.

Karanasiou, A., Viana, M., Querol, X., Moreno, T., Leeuw, F. De. (2014) Science of the Total Environment Assessment of personal exposure to particulate air pollution during commuting in European cities - Recommendations and policy implications. Science of Total Environment, 490, 785-797. https://doi.org/10.1016/j.scitotenv.2014.05.036

Kumar, P., Patton, A.P., Durant, J.L., Frey, H.C. (2018) A review of factors impacting exposure to $PM_{2.5}$, ultra fine particles and black carbon in Asian transport microenvironments. Atmospheric Environment, 187, 301-316. https://doi.org/10.1016/j.atmosenv.2018.05.046

Li, F., Lee, E.S., Liu, J., Zhu, Y. (2015) Predicting self-pollution inside school buses using a CFD and multi-zone coupled model. Atmospheric Environment, 107, 16-23. https://doi.org/10.1016/j.atmosenv.2015.02.024

Morales, R., Galvis, B., Balachandran, S., Ramos-Bonilla, J.P., Sarmiento, O.L., Gallo-Murcia, S.M., Contreras, Y. (2017) Exposure to fine particulate, black carbon, and particle number concentration in transportation microenvironments. Atmospheric Environment, 157, 135-145. https://doi.org/10.1016/j.atmosenv.2017.03.006

Morales, R., Galvis, B., Rincón-riveros, J.M., Rincón-caro, M.A., Rodriguez-valencia, A., Sarmiento, O.L. (2019) Personal exposure to air pollutants in a Bus Rapid Transit System: Impact of fleet age and emission standard. Atmospheric Environment, 202, 117-127. https://doi.org/10.1016/j.atmosenv.2019.01.026

NASA-Langley Research Center, n.d. NASA-Turbulence Modeling Resource [WWW Document]. 2017-03-08. URL turbmodels.larc.nasa.gov/

Observatorio Ambiental de Bogotá, O. (2017) Informe mensual de Calidad del Aire en Bogotá.

Piccirilo, J.M. (2012) Qué es un BRT, o la implementación del Metrobús en la ciudad de Buenos Aires, Argentina. Boletín FAL, 312, 10.

Satiennam, T., Fukuda, A. (2006) A Study on the Introduction of Bus Rapid. International Association of Traffic and Safety Sciences, 30, 59-69. https://doi.org/10.1016/S0386-1112(14)60170-9

Strasser, G., Hiebaum, S., Neuberger, M. (2018) Commuter exposure to fine and ultrafine particulate matter in Vienna. Wien Klin Wochenschr The Central European Journal of Medicine, 130, 62-69. https://doi.org/10.1007/s00508-017-1274-z

Versteeg, H.K., Malalasekera, W. (1995) An Introduction to Computational Fluid Dynamics - The Finite Volume Method. Fluid flow handbook. McGraw-Hill. https://doi.org/10.2514/1.22547

World Health Organization (2006) WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Geneva World Health Organization. https://doi.org/10.1016/0004-6981(88)90109-6

Wright, L. (2005) Bus Rapid Transit. Transportation Research Board, 52, 1-88.

Wyzga, R.E., Rohr, A.C. (2015) Long-term particulate matter exposure: Attributing health effects to individual PM components. Journal Air Waste Management Association, 65, 523-543. https://doi.org/10.1080/10962247.2015.1020396

Xu, B., Hao, J. (2017) Air quality inside subway metro indoor environment worldwide: A review. Environment International, 107, 33-46. https://doi.org/10.1016/j.envint.2017.06.016

Zapata, S., Castaneda, M., Garces, E., Franco, C.J., Dyner, I. (2018) Assessing security of supply in a largely hydroelectricity-based system: The Colombian case. Energy, 156, 444-457. https://doi.org/10.1016/j.energy.2018.05.118