

RESEARCH ARTICLE

Engineering

NANOPARTICLES MEASUREMENT IN ELECTRIC, GAS, AND DIESEL BUSES IN BOGOTÁ COLOMBIA MASS TRANSPORTATION SYSTEM

MEDICIÓN DE NANOPARTÍCULAS EN ELECTRICIDAD, GAS, Y AUTOBUSES DIESEL EN BOGOTÁ COLOMBIA EN EL SISTEMA DE TRANSPORTE MASIVO

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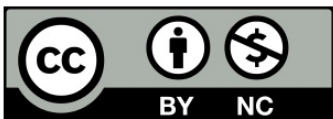
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Abstract. The sustainability for urban contexts is a very important objective today, and it needs to be linked transversally to all processes of technological change that impact people and the territory. In this study, we compare the nanoparticles measured inside diesel, gas, and electric buses during their normal operation in Bogota, Colombia. We used a miniature diffusion size classifier (DiSCmini) to measure nanoparticles concentrations, average particle size, and lung-deposited surface area. Our results revealed significantly lower levels of this pollutant inside electric buses. The concentration of nanoparticles per cubic centimeter is about 41% and 27% lower in electric buses compared to diesel and gas respectively. The lung-deposited surface area is also lower in electric buses. Nevertheless, average particle size in electric buses is 10% and 18% smaller compared to diesel, and gas respectively. The results of this study are important because they show useful information for future selection processes of bus technologies for public passenger transport in other cities around the world; This research provides information resources that can be used in technical evaluation processes that link the possible effects on the health of users and the environment, and favor concepts for the improvement of sustainability.

Keywords: Diesel buses, BEV electric buses, CNG compressed natural gas buses, nanoparticles, LDSA lung deposited surface area, mass transit system.

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Resumen

La sostenibilidad para los contextos urbanos es un objetivo muy importante hoy en día, y debe vincularse transversalmente a todos los procesos de cambio tecnológico que impactan a las personas y al territorio. En

este estudio comparamos las nanopartículas medidas dentro de los autobuses diésel, de gas y eléctricos durante su operación normal en Bogotá, Colombia. Usamos un tamaño de difusión en miniature, clasificador (DiSCmini) para medir concentraciones de nanopartículas, partículas promedio tamaño del cle y área de superficie depositada en los pulmones. Nuestros resultados revelaron significativamente niveles más bajos de este contaminante dentro de los autobuses eléctricos. la concentración de nanopartículas por centímetro cúbico es aproximadamente un 41% y un 27% menor en electricidad autobuses en comparación con el diésel y el gas, respectivamente. La superficie depositada en los pulmones. La superficie también es menor en los autobuses eléctricos. Sin embargo, el tamaño medio de las partículas en Los autobuses eléctricos son un 10% y un 18% más pequeños en comparación con el diésel y el gas, respectivamente. Los resultados de este estudio son importantes porque muestran información útil para futuros procesos de selección de tecnologías para el transporte público de pasajeros en otras ciudades del mundo; esta investigación proporciona fuentes de información que pueden ser utilizadas en procesos de evaluación técnica. que relacionan los posibles efectos sobre la salud de los usuarios y el medio ambiente, y favorecer conceptos para la mejora de la sostenibilidad.

Palabras clave: autobuses diésel, autobuses eléctricos BEV, gas natural comprimido GNC autobuses, nanopartículas, superficie depositada en los pulmones de LDSA, sistemas de transporte masivo.

1 | INTRODUCTION

Air pollution in urban environments has become of increasing concern, especially after evidence of significant health impacts caused by air pollutants concentrations previously regarded as acceptable [1]. Of the many microenvironments in cities, the ones linked to mass transit may be where more city dwellers are exposed to higher concentrations of traffic-related air pollutants (TRAP) [2], [3], [4], [5], [6], [7], [8], [9]. Most mass transit systems use buses that could be considered heavy-duty vehicles. Euro VI and Euro V diesel buses equipped with diesel particulate filters (DPF), Compressed Natural Gas (CNG) powered and battery electric vehicles (BEV) buses have become common in mass transit systems of many cities during the last decade [10], [11], [12], [13]. Heavy-duty vehicles play a significant role in particulate matter emissions inventories on the roads of many cities [14], [15], [16], [17], [18], and diesel engines are the main emitters of ultrafine particles in urban areas [19], [20], [21], [22]. Natural gas vehicles may emit less soot and particulate by mass but likely more particles by number [23], [24], [25], which may have more important health effects than the larger ones likely due to a larger ratio of surface area to mass [26], [27], [28]. Fewer studies have looked at nanoparticles from BEV vehicles, but non-exhaust particulate from BEV vehicles could on occasion exceed particulate emissions from internal combustion engines [29], [30], [31]. In Bogotá, a city with more than seven million residents, the mass transit system had approximately 9400 buses by 2021, using different technologies. The evolution of the distribution of bus technologies is shown in Table 1. In 2021, 470 new BEV buses started operation in Bogotá, and it is expected that by the end of 2022, the city will have approximately 1500 BEV buses. Concentrations of fine particulate and black carbon inside Bogota's bus rapid transit (BRT) system, a part of the city's mass transit system (see tab. 1), improved by approximately 80%, after 2020 because of the fleet upgrade with diesel EURO V buses with particulate filters, and EURO VI CNG buses [11]. Mainly old EURO II / III buses were replaced during the fleet upgrade. This could have had a positive effect on reducing nanoparticle exposure levels, but their measurements did not include BEV buses that started operations after January 2021. In this work, we analyzed the concentration, the average size, and the lung-deposited surface area of nanoparticles measured exposure inside diesel, CNG, and BEV buses of the zonal component of Bogotá's mass transit system, during their normal operation, to determine if differences in bus technology, impact commuter's exposure to nanoparticles.

TABLE 1 Bogota's mass transit fleet technology share

Technology	2013	2015	2017	2020	2022
<Euro IV	1338	3148	2703	1824	749
Euro IV	138	983	964	972	986
Euro V	125	2369	2666	2656	3327
HYbrid		56	56	56	56
Euro VI - CNG			3	2498	1490
BEV			1	484	1128

2 | METHODS AND DATA

2.1 | Study domain

The mass transit system in Bogotá has two components BRT (Bus Rapid Transit) and zonal component. The BRT which operates articulated, bi-articulated buses on exclusive lanes and single-body buses that feed end-of-line stations on mixed traffic lanes (see 1); and a zonal component that uses single-body buses, operates a mix of diesel, CNG, hybrid (diesel-BEV) and BEV buses mainly on mixed traffic lanes (see 2). For this study, we measured exposure inside diesel, CNG, and BEV buses of the zonal component buses operating on Carrera 13 route which runs from West to East, covering the localities of Fontibón, Kennedy, Puente Aranda, Los Mártires, Antonio Nariño, and Santa Fe (see Fig. 3). Tab. 2 shows the lines and bus routes selected and the bus technologies. Measurements were made by a person carrying the instruments with the inlet nozzle located on the breathing zone and free of obstructions. The person always traveled at the back between the second and third doors of the buses (see 2). This area receives the largest number of users and is closer to the engines. The data were collected every 10 seconds. The measurement days were selected looking for average operating conditions and only during business days. We measured outside the hours of vehicular restrictions, during average weather conditions for the city, not very heavy rains. Days with any atypical events such as protests, or car-free days were not included. We measured exposure inside single-body buses for 80 passengers, for all three technologies. We checked that diesel and CNG buses measured did not have any type of post-treatment or filter installed to control emissions. Tab.3 shows the information about the buses tested.

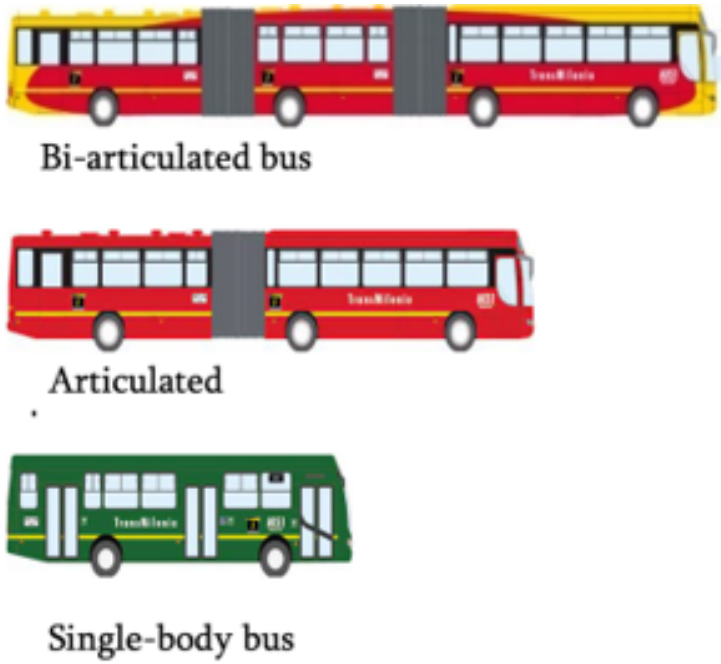


FIG. 1 Buses used by the BRT component

80 passenger single-body buses

50 passenger single-body buses

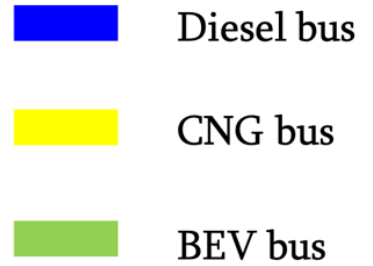


FIG. 2 Buses used on the zonal component

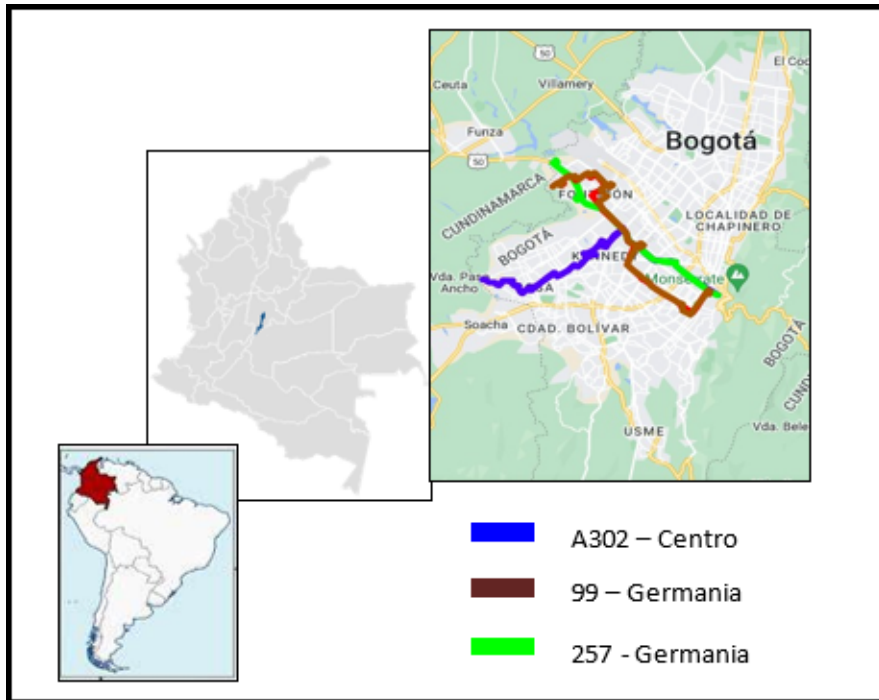


FIG. 3 Selected routes in Bogotá in Colombia

TABLE 2 Bus routes measured

Route Name	Bus Technology	Bus stops	Origin	Destination
A302 - Centro	BEV	62	Kr 123 - Cl 14 / Fontibon	AC 19 - Kr 9 / Las Nieves
99 - Germania	Gas	64	Tv 80i - Dg 89 b South / Bosa	AC 19 - Kr 4 / Las Nieves
257 - Germania	Diesel	37	Cl 17d - K135 / Fontibon	AC 19 - Kr 5 / Veracruz

TABLE 3 Measured buses

Bus Technology	Standard	Brand	last oil change (km)	Date of monitoring	Direction *	Total rides
BEV	BEV	BYD	8.174	05/05/2021	E-W	1
BEV	BEV	BYD	7.140	13/05/2021	E-W / W-E	2
BEV	BEV	BYD	9.327	20/05/2021	E -W	1
CNG	Euro VI	Volkswagen	11.320	07/05/2021	W-E	1
CNG	Euro VI	Volkswagen	6.908	13/05/2021	E -W / W-E	2
CNG	Euro VI	Volkswagen	12.730	21/05/2021	E -W	1
Diesel	Euro VI	Volvo	4.600	20/05/2021	E -W / W-E	2
Diesel	Euro VI	Volvo	5.230	25/05/2021	E -W / W-E	2

*E: East / W: West

2.2 | Instruments

We used the miniature diffusion size classifier - DiSCmini (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) portable device to measure the number concentrations ($\#cm^{-3}$) of particles between 10 to 700 nm in size. The instrument also reports the mean nanoparticle diameter (nm), and the lung-deposited surface area m^2cm^{-3} with a frequency of $0.1Hz$.

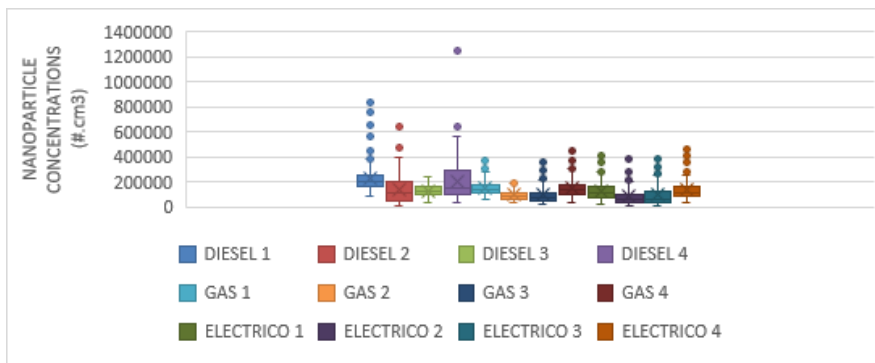
3 | RESULTS AND DISCUSSION

In the case of BEV buses, we measured during 4 dates, 3 in the W-O direction and 1 in the O-W direction. In total 177 minutes and 37.24 km. The average nanoparticle concentration by cubic centimeter was $108519.5cm^{-3}$, the mean nanoparticle diameter was $35.2nm$, and the lung-deposited surface area average was $191.6\mu m^2cm^{-3}$. In the case of Diesel buses, we did 4 measurements, 2 in the W-O direction and 2 in the O-W direction. In total 225 minutes and 47.62 km. The average nanoparticle concentration was $166558.6cm^{-3}$, the mean nanoparticle diameter was $37.2nm$, and the lung-deposited surface area average was $344.31\mu m^2cm^{-3}$. Finally, in the case of CNG buses, were recorded 4 measurements, 2 in the W-O direction and 2 in the O-W direction. In total 233.4 minutes and 51.45 km. The average nanoparticle concentration was $142920.8cm^{-3}$, the mean nanoparticle diameter was $42.39nm$, and the lung-deposited surface area average was $318.5\mu m^2.cm^{-3}$. Tab. 4 shows a summary of the data. Figure 1 shows nanoparticle concentrations for these buses:

TABLE 4 Summary data

Bus technology	BEV	CNG	DIESEL
Total data	841	929	851
Average nanoparticle concentration ($\#cm^{-3}$)	109773,0	124075,6	175000,5
Max	492263	495730	1247418
Min	13556	18590	14526
Average nanoparticle diameter (nm)	35,2	42,7	37,6
Average LDSA μm^2cm^{-3}	195,0	281,5	349,6

FIG. 4 Nanoparticle concentration results in the measurement sessions described in Table 3 for Diesel, Gas and electric bus technologies



The exposure concentration of nanoparticles in BEV buses is lower than in CNG and diesel buses (See Tab 5). The average diameter of nanoparticles is greater in CNG buses than in diesel and BEV buses. The average lung-deposited surface area is lower in BEV buses than in the other two technologies (See Tab. 6). These results are consistent with studies that have been previously conducted in cities such as Arnhem, Netherlands,

and Como, Italy, where it was concluded that High UFP concentrations are often found in diesel buses [32], [33]. By contrast, concentrations in compressed natural gas buses [34], [7] and electric buses are relatively low [35]. Mode of transport, as well as the commuting route and type of vehicles, plays an influential role in the exposure levels of particulate matter [33]. The average diameter of the nanoparticles is not directly proportional to the concentration per cubic centimeter or the lung-deposited surface area. Nanoparticle count and lung-deposited surface area are proportional in the different bus technologies; see Figs. 5 - 7

TABLE 5 Average results per bus technology

Technology	Average Nanoparticle concentration ($\#cm^{-3}$)	Average particle size (nm)	Average lung-deposited surface area $\mu m^2 cm^{-3}$
BEV	108519.4	35.2	191.6
CNG	121904.9	42.4	273.9
Diesel	166558.6	37.2	344.3

TABLE 6 Comparison of the results per bus technology

Comparative	Average number $m^2 cm^{-3}$	Average nanoparticle diameter (nm)	Average lung-deposited surface area $\mu m^2 cm^{-3}$
BEV Vs Diesel	-41%	-10%	-48%
BEV Vs CNG	-27%	-18%	-39%

FIG. 5 Nanoparticle concentration vs lung-deposited surface area in BEV buses

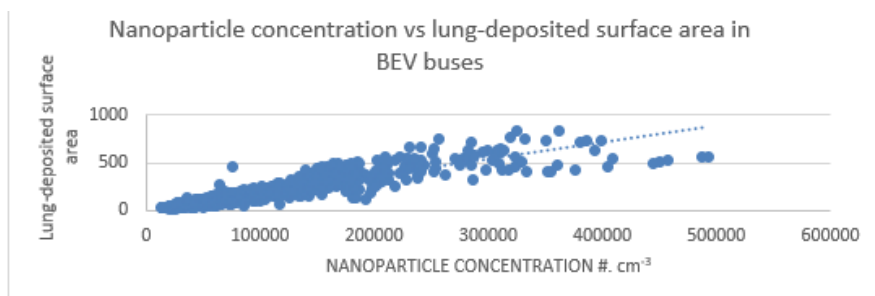


FIG. 6 Nanoparticle concentration vs lung-deposited surface area in CNG buses

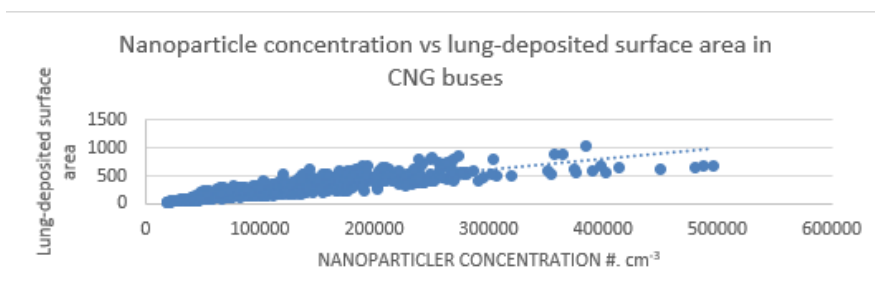
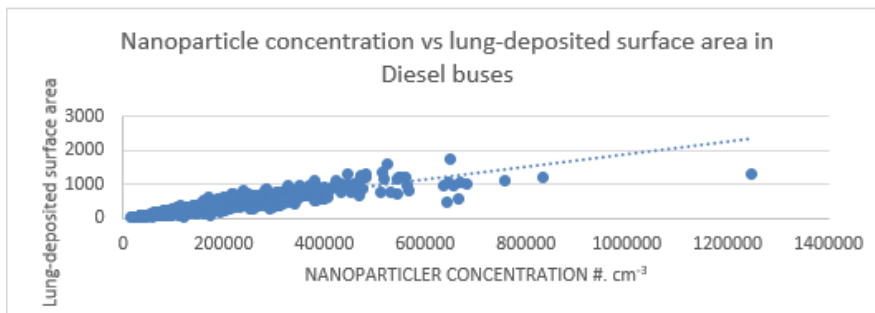


FIG. 7 Nanoparticle concentration vs lung-deposited surface area in Diesel buses

Considering the combustion of lubricating oil as an important source of particle formation in CNG and Diesel engines [32], the age of the lubricating oil of the engine could have some impact on the particle concentration in diesel and CNG buses. According to our results, a direct proportionality between this parameter and the nanoparticle concentration per cubic centimeter in diesel, CNG, and BEV buses is not clear. For BEV buses, although nanoparticle concentration is lower on average, it can be as high as CNG and diesel buses at some points along the route, because the concentration can be impacted by other variables than the bus technology, for example, the urban pollution, other vehicles, and other sources, this is deduced by some peaks resulting from doors opening at bus stops, this phenomenon was also presented in similar studies in cities such as Barcelona or Beijing [36]; [37], frequently, “stop-start” and door opening in journeys would increase opportunities for air infiltration, even when windows are closed [35]; [33]. Data shows that the higher speeds could reduce the concentration of nanoparticles per cubic centimeter in the BEV buses, contrary to CNG and diesel buses. However, this also leads to an increase in the diameter and lung-deposited surface area. The particle levels in buses in this study were higher than in other cities, including Basel, Switzerland [34, p. 4-5], Arnhem, Netherlands [?], Italy [32] and Helsinki, Beijing, China [38], Barcelona, Spain [36] the proportion of the results was only similar to studies in Milan, Italy [39] and Santiago, Chile [40]. The differences can result from many factors such as traffic conditions, bus technology, and urban air pollution concentration in the different cities, but also from bus ventilation (fans, air conditioning, open windows, and others).

4 | CONCLUSIONS

This study was the first to compare the exposure to traffic-related nanoparticles, inside three bus technologies: Diesel, CNG, and BEV, in Bogotá, a megacity in Colombia. The concentration of nanoparticles per cubic centimeter in BEV buses is 27% and 41% lower than in CNG and diesel buses respectively, this can increase the risk of health effects by irritation of the respiratory tract and lungs, also it can greater susceptibility to respiratory infections and it can to aggravate the symptoms in patients with chronic diseases. The average diameter of nanoparticles in BEV buses is 18% and 10% lower than in CNG and diesel buses respectively. Finally, the average lung deposited surface area in BEV buses is 39% and 48% lower than in CNG and diesel buses, this could push changes in diseases related to the circulatory system, because the nanoparticles size could allow advancing into the bloodstream (Navarro, Meza, Soto, Castañeda, Pedroza, 2021). The right of all humans to an adequate environment for their health and well-being generates the need to link variables associated with sustainability in all processes of technological advancement. The selection processes of bus technologies for public passenger transport in urban contexts must review not only financial and technical variables, but must also analyze possible risks to the health of users and other actors, they must also include environmental impact assessment processes. Exposure to nanoparticles in diesel buses is alarming as our measurements confirm, and the problem is more serious if we consider that diesel fleet is widely used in many megacities. Therefore, it is important for policymakers to improve bus transportation systems, mainly by switching from diesel to cleaner power. As travel times are not likely to decrease in cities like Bogota, the observed reductions in nanoparticles with BEV could imply a decrease in the potential health effects for users, and this could have important effects

on public health policies and projects of great impact in big cities. It's necessary to carry out a comparative analysis between diesel, CNG, and BEV buses for other types of buses. Also, it is necessary to analyze other variables on the comparative between the different technologies, for example, temperature, sound, vibrations, and others. Finally for future research is good to include the bus users, to check their perceptions.

5 | ACKNOWLEDGMENTS

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