Impact of the transport system on air quality: the case of Rio de Janeiro, Brazil

Impacto do sistema de transporte na qualidade do ar: o caso do Rio de Janeiro, Brasil

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ABSTRACT

In the downtown area of Rio de Janeiro, Brazil, an urban mobility plan was implemented between 2011 and 2016 due to the 2014 Fifa World Cup and the 2016 Olympic Games. This study aimed to evaluate the environmental benefits achieved by this urban mobility plan by comparing two periods: 2013 (before the megaevents) and 2017 (after the megaevents). Energy consumption and emissions from buses were estimated, and regulated pollutants (O_3, CO, PM_{10}, and $PM_{2.5}$) were monitored. According to the calculations, NOx was the most emitted pollutant (62% of the total 20 tons). A 25% reduction in levels for all pollutants was observed in 2017 compared to 2013. The reorganization of traffic shortened the bus routes, resulting in less fuel consumption (8%) and emissions. The annual mean concentrations of air pollutants (PM_{10}, $PM_{2.5}$, and CO) also decreased, improving air quality. However, the levels of O_3 increased, possibly owing to the reduction of NO_x levels.

Keywords: Air quality. Urban mobility. Light-rail transit. Pollutant emissions.

RESUMO

No centro da cidade do Rio de Janeiro, Brasil, foi implementado um plano de mobilidade urbana entre 2011 e 2016 devido à Copa do Mundo Fifa 2014 e aos Jogos Olímpicos 2016. Este estudo teve como objetivo avaliar os benefícios ambientais alcançados por esse plano de mobilidade urbana comparando dois períodos: 2013 (antes dos megaeventos) e 2017 (depois dos megaeventos). O consumo de energia e as emissões dos ônibus foram estimados e os poluentes regulamentados (O_3, CO, PM_{10} e $PM_{2,5}$) foram monitorados. De acordo com os cálculos, o NO_x foi o poluente mais emitido (62% do total de 20 t). Observou-se em 2017 uma redução de 25% de todos os poluentes em relação a 2013. A reorganização do tráfego encurtou as rotas de ônibus, resultando em menor consumo de combustível (8%) e emissões. As concentrações médias anuais de poluentes atmosféricos (PM_{10}, $PM_{2,5}$ e CO) também diminuíram, melhorando assim a qualidade do ar. No entanto, os níveis de O_3 aumentaram, possivelmente devido à redução dos níveis de NOx.

Palavras-chave: *Qualidade do ar. Mobilidade urbana. Trânsito ferroviário leve. Emissões poluentes.*

1 INTRODUCTION

Numerous studies were carried out in the metropolitan region of Rio de Janeiro (MRRJ) before, during and after the 2014 Fifa World Cup and the 2016 Olympic Games to assess air quality (*e.g.*, DE LA CRUZ *et al.*, 2019; GOMES *et al.*, 2018, JUSTO et al., 2020; VENTURA *et al.*, 2019a, b). However, the relationship between air quality, urban mobility, and fuel use has not been examined. Motor vehicles release various pollutants that are detrimental to people and the environment, primarily due to fossil fuel combustion (GUO *et al.*, 2013; LI *et al.*, 2011; VENTURA *et al.*, 2020; WANG *et al.*, 2010). In this context, this study aimed to investigate how the mobility management strategies implemented probably affected the air quality in Rio de Janeiro's downtown. The principal focus was on greenhouse gases (GHGs: carbon dioxide [CO_2] and methane [CH_4]) and regulated air pollutants (nitrogen oxides [NO_x], carbon monoxide [CO], particulate matter [PM_{10} and $PM_{2.5}$] and tropospheric ozone [O_3]), which are primarily caused by bus emissions. The most appropriate way to assess this impact is through monitoring the air quality of areas mostly impacted by this modal and also through estimates of energy consumption and pollutant emission scenarios due to the burning of fuels on the roads of the study region. Bus energy consumption and emissions were assessed in two scenarios: before (2013) and after (2017) the aforementioned megaevents, with regulated pollutants being tracked from 2013 to 2017.

It is important to emphasize that vehicles are the primary atmospheric pollutants in Rio de Janeiro, especially in the downtown area (INEA, 2016a, b). Therefore, appropriate traffic management solutions can help to reduce emissions and avoid traffic bottlenecks, lowering energy consumption. These solutions can also mitigate atmospheric gas (CO2, CH4, CO, NOx) and particles with aerodynamic diameter less than 10µm and 2.5µm (PM10 and PM2.5) emissions, enhancing social well-being. Fine particles (PM2.5) and certain gases (O3, NO2) are the principal pollutants of global concern for respiratory and cardiovascular disorders (GUO *et al*., 2013; LI *et al*., 2011; WANG *et al*., 2010). Since there are few monitoring stations in Brazil, there is limited research on urban mobility and air quality. But Rio de Janeiro has the oldest and, currently, the second-largest air quality monitoring network in Brazil (GIODA *et al*., 2016). As a result, the findings presented in this study are unprecedented and were achieved in collaboration with the government's environmental monitoring agency.

1.1 URBAN MOBILITY IN RIO DE JANEIRO

More than 80% of the Brazilian population lives in urban areas. Therefore, mobility is a critical issue to be considered by governments. Rio de Janeiro's uniqueness lies in the large urban area with a fast-rising population, which necessitates innovative urban mobility solutions for a variety of modes of transportation, including automobiles, buses, light-rail vehicles (LRVs), trams, trains, subways, ferries, and bicycles (ALMEIDA *et al.*, 2017; IZAGA, 2014; LINDAU *et al.*, 2016; MALHEIROS *et al.*, 2017). About 53% of the population uses public transportation, which provides appropriate transportation solutions. However, to travel the same distance, a ride on public transport takes roughly 40 min longer than driving (SETRERJ, 2003). Improvements in public transportation networks can result in more sustainable urban mobility and improved quality of life. Between 2011 and 2016, the MRRJ underwent structural improvements to host the 2014 Fifa World Cup and the 2016 Olympic Games (GATO; SALAZAR, 2018; SANTOS NETO *et al.*, 2018, VENTURA *et al.*, 2019a). Several areas of Rio de Janeiro's downtown were restored, including the port sector (Porto Maravilha), which covers 5 km² (Rio de Janeiro, 2009). The regeneration was foreshadowed in the region's municipal mobility plan, which includes restoring the urban infrastructure, the environment, and the region's historical and cultural assets (GOMES *et al.*, 2018; PORTO MARAVILHA, 2021). The Perimetral road was replaced by an expressway connecting downtown to the airport and major roads via a new urban tunnel (Marcelo Alencar's tunnel), which is the world's largest. Furthermore, a new road (Via Binário do Porto) was built to connect to a new tunnel (Rio 450 tunnel) (GATO; SALAZAR, 2018; PORTO MARAVILHA, 2021; SANTOS NETO *et al.*, 2018). The region's automobile circulation was improved due to these changes (Table 1).

Table 1 | Interventions implemented in the municipal urban mobility plan for the downtown area of Rio de Janeiro

Interventions	*Civil work period*	*Extension (km)*	*Lanes/ direction*	*Benefits*
Perimetral viaduct's demolition	November 2013 to April 2014	1.1 and 0.3	4	To amplify the vehicle circulation and revitalize the Port region
Expressway Via's construction	May 2014 to June 2016	1.6	3	To receive up to 110 thousand vehicles per day
Marcelo Alencar's tunne construction	October 2012 to June 2016	3.4	3	
Via Binário do Porto road's construction	September 2011 to November 2013	3.5	3	To receive up to 110 thousand vehicles per day
Rio450 tunnel's construction	October 2011 to March 2015	1.5	3*	To receive up to 55 thousand vehicles per day
Light-rail vehicles (LRVs)'s implementation	June 2016	24	-	Transport 300 thousand people per day
Providência Cable car terminal	July 2011 to July 2014	0.7	-	Offer mobility to almost 5,000 residents of the Morro da Providência community
Bike paths	February 2014 to June 20161	17	-	To offer the use possibility of this clean modal transport in this region

Note: *only one direction

Source: Porto Maravilha, 2021; ¹ Veja-Rio, 2017

Additionally, LRVs integrate all modes of downtown transportation, including ferries, cableways, and cruise ships. In addition, two smaller lines were constructed: line 2 (1.8 km) and line 3 (1.8 km) (PORTO MARAVILHA, 2021; VLT RIO, 2019). In this area, 32 LRVs traverse 28 km on a trail network with intervals ranging from 3 to 15 min with stop stations every 400 m. LRVs emit no pollutants into the atmosphere. In the downtown area, automobile and bus lanes have been replaced with LRVs and Bus Rapid Service (BRS) lines, which only allow buses and taxis to travel (ALMEIDA *et al*., 2017; SMTR, 2016), along with the installation of bike paths (ALMEIDA *et al.*, 2017; SMTR, 2016). Based on these considerations, assessing the impact of changes in urban mobility on air quality is essential to know whether the measures taken are effective.

2 MATERIALS AND METHODS

This study aimed to understand how the urban mobility strategy established to host the megaevents affected air quality in Rio de Janeiro's downtown. Two periods were considered: i) 2013: the year before the megaevents, when various mobility improvements were still being implemented; ii) 2017: the year following the megaevents, when the transportation system upgrades were completed. Vehicle emissions (2.1), energy usage (2.2), and air quality monitoring were the three primary metrics utilized to analyze the environmental consequences caused by automobiles over these periods (2.3). Based on the distance travelled, vehicle and energy usages were calculated. Unfortunately, only data for buses was available and only for the years 2013 and 2017. In contrast, air pollutant levels were monitored continuously from 2013 to 2017.

2.1 VEHICLE EMISSION ESTIMATES

The Traffic Company of Rio de Janeiro submitted daily vehicle flow data to examine emissions from the downtown district before (2013) and after (2017) the reorganization of urban mobility (CET-Rio). The 1) Passos (400 m), 2) Presidente Antônio Carlos (850 m), 3) Rio Branco (650 m), and 4) 1o March (400 m) avenues were the routes used in this investigation. Between 2013 and 2017, these were the only routes in the city that were monitored. However, because they have a similar traffic flow to neighbouring streets, they are seen as emblematic of the region. The study of Li et al. (2019) was limited in this sense because the authors only looked at four specific road segments with traffic detectors. However, the data could fully represent the impacts of transport.

Inea Resolution No. 67 was utilized to compute highway emissions (INEA, 2013). It outlines a process for developing regional inventories of automobile emissions. As shown in Equation 1, this method uses a bottom-up strategy to predict vehicle emissions.

$$Ei = \sum_i N \times Fi \times d \qquad \text{(eq. 1)}$$

Where,

Ei: Vehicle emission of air pollutant i, in kg day-1;

N: Vehicle flow, in vehicles/day;

d: Distance travelled in the stretches under study, in km;

Fi: Average emission factor of the air pollutant i, in kg km-1.

Municipal ordinances restrict running trucks during periods of heavy traffic flow on the routes chosen, so only urban buses were used to calculate the emissions. Buses were expected to be constructed in 2012 or later, employing technology comparable to that used in the EURO5 standard (CONAMA, 2008). Vehicle emission factors for the Rio de Janeiro bus fleet are shown in Table 2.

Table 2 | Emission factors per pollutant for urban buses of the P7 category and the bus fleet of Rio de Janeiro city for Manufacture year

Manufacture years	*CO (g km-1)*	*NOx (g km-1)*	*PM10 (g km-1)*	*CH4 (g km-1)*	*CO2 (g km-1)*	*Urban buses fleet*
2012	0.54	2.62	0.02	0.06	1.27	859
2013	0.54	2.69	0.02	0.06	1.28	497
2014	0.54	2.69	0.02	0.06	1.28	346
2015	0.48	2.62	0.02	0.06	1.28	437
2016	0.57	2.90	0.02	0.06	1.26	296
P7 (weighted)	0.53	2.68	0.02	0.06	1.27	2,435

Source: Adapted from Cetesb (2016) and Detran-RJ (2018)

2.2 ENERGY CONSUMPTION ESTIMATES

The Municipal Transportation Department supplied information on the operation of city bus services, such as line numbers, monthly distance travelled (km), number of trips paid, and number of passengers transported (SMTR, 2019a). This application programming interface (API) developed by IplanRio company keeps track of the city bus fleet's GPS fitted in vehicles (SMTR, 2019b). In addition, the Federation of Passenger Transport Companies of Rio de Janeiro State provided data on average monthly bus fuel consumption (L km^{-1}) (FETRANSPOR, 2017). Two scenarios [scenario 1 (2013) and scenario 2 (2017)] were created for the evaluation of the energy consumption for a typical month (j = May), that is, a month that does not include school holidays or holidays with a significant influence on traffic, such as Carnival. To compute the energy consumption in each scenario, the monthly distance travelled by the lines that traverse Rio de Janeiro's downtown was first estimated using Equation 2.

$$DMD_{ji} = \sum_{n} DLMD_{ji} \qquad \text{(eq. 2)}$$

Where,

DMD_{ji}: Distance travelled by bus lines in downtown of Rio de Janeiro in month j of year i, in m

$DLMD_{ji}$: Distance travelled by each bus line (n) in downtown of Rio de Janeiro in month j of year i, in meters.

According to Equations 3 and 4, these distances were computed using Google Earth and .kmz files containing all the bus lines (SMTR, 2015).

$$PLD = (DLT/DLD) \times 100 \qquad \text{(eq. 3)}$$

$$DLMD_{ji} = DLM_{ji} \times PLD \qquad \text{(eq. 4)}$$

Where,

PLD: Percentage of the route of each bus line in downtown of Rio de Janeiro, in %

DLT: Total route distance of each bus line in meters

DLD: Distance of the route of each bus line in downtown of Rio de Janeiro, in meters

$DLMD_{ji}$: Distance travelled by each bus line in downtown of Rio de Janeiro in month j of year i, in meters

DLM_{ji}: Distance travelled by each bus line in month j of year i, in meters

Equations 5, 6, and 7 were used to compute the fuel consumption (CFji) and the volumes of mineral diesel (CDMji) and biodiesel (CBji). In May 2013, the percentage of biodiesel in mineral diesel was 5%, while in May 2017, it was 7% (BRAZIL, 2016; CNPE, 2009).

$$CF_{ji} = DMD_{ji} \times FA \qquad \text{(eq. 5)}$$

$$CDM_{ji} = (1-p_i) \times CF_{ji} \qquad \text{(eq. 6)}$$

$$CB_{ji} = (p_i) \times CF_{ji} \qquad \text{(eq. 7)}$$

Where,

CF_{ji}: Diesel Commercial fuel consumption in month j of year i, in Liters

DMD_{ji}: Distance travelled by bus lines in downtown of Rio de Janeiro in month j of year i, in meters

FA: fuel autonomy, in L m^{-1}

CDM_{ji}: Mineral diesel consumption in month j of year i, in Liters

p_i: biodiesel percentage in commercial fuel in month j of year i, in %

CB_{ji}: biodiesel consumption in month j of year i, in Liters

Equations 8, 9, and 10 were used to compute the total usable energy consumption after calculating mineral diesel and biodiesel monthly consumptions in each scenario.

$$CEU_{dMji} = DE_{DM} \times CDM_{ji} \qquad \text{(eq. 8)}$$

$$CEU_{Bji} = DE_{B} \times CDM_{ji} \qquad \text{(eq. 9)}$$

$$CEU_{Tji} = CEU_{dMji} + CEU_{Bji} \qquad \text{(eq. 10)}$$

Where,

CEU_{dMji}: Useful energy consumption of mineral diesel in month j of year i, in MJ/month

DE_{DM}: Energy density of mineral diesel, in tep m^{-3}

CEU_{Bji}: Useful energy consumption of biodiesel in month j of year i, in MJ/month

DE_{B}: Energy density of biodiesel, in tep m^{-3}

CEU_{Tji}: Total useful energy consumption in month j of year i, in MJ/month

2.3 AIR QUALITY MONITORING

The Carioca (-22.908344/-43.178151) automated station collects meteorological parameters, PM_{10}, CO and O_3. In addition, the Castelo (-22.90752/-43.17257) semiautomatic station collects particulate matter (PM_{10} and $PM_{2.5}$). Both sites are in commercial areas, and vehicles are the primary source of pollution (INEA, 2016b; SMAC, 2013). Both stations were monitored from 2013 to 2017.

Carioca station has a full coverage radius of 2 km and a partial coverage radius of 400 m (SMAC, 2013). Castelo stations have a radius of 500 m (SEA, 2011) (Figure 1).

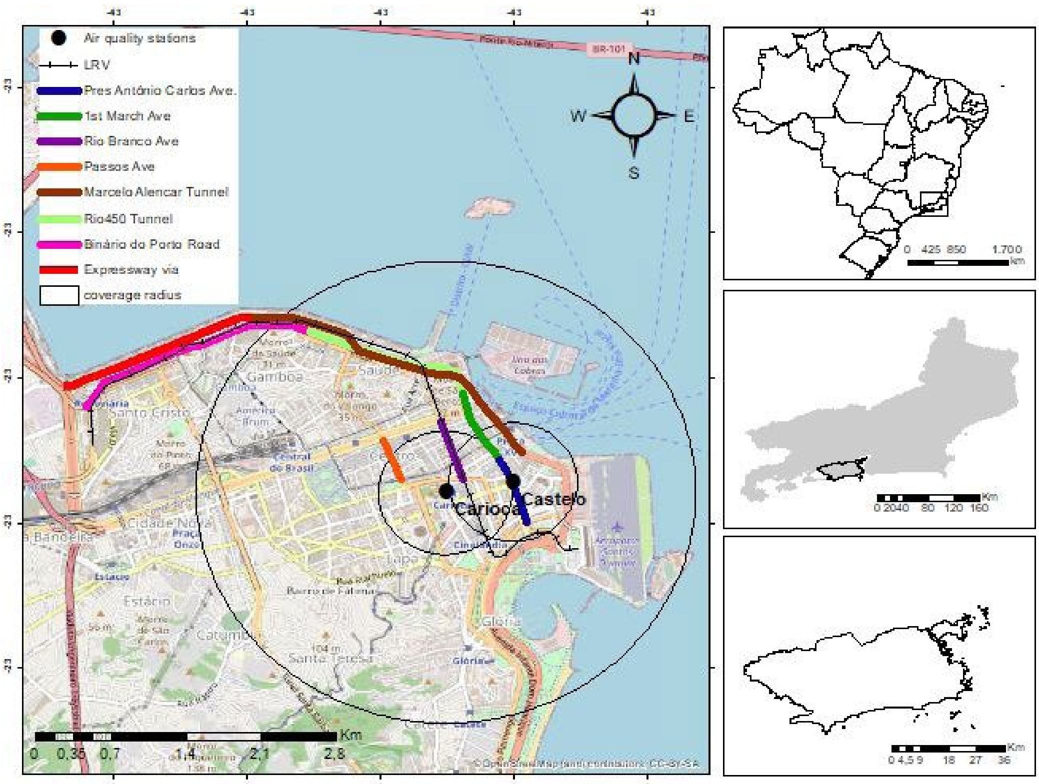

Figure 1 | Aerial view of the coverage radius of the air quality monitoring stations in downtown Rio de Janeiro: 1) Carioca station and 2) Castelo station

Source: Authors

An Ecotech Spirant BAM analyzer using the beta attenuation method was employed to quantify the PM with a diameter < 10 µm (PM_{10}) at the Carioca station. An Ecotech Serinus 30 analyzer with infrared detection was used to evaluate carbon monoxide (CO). Ozone (O_3) was measured using an Ecotech Serinus 10 analyzer that uses the EQOA-0506-160 Reference Method. As this station is automatic, data is provided hourly, except for O_3 data that are provided at each 8 h. Castelo's semi-automatic stations use samplers (Energética, Brazil, models AGVMP10 and AGVMP252) to monitor PM in the coarse (PM_{10}) and fine ($PM_{2.5}$) fractions, for 24 h every six days, encompassing all days of the week, including weekends and wet days (INEA, 2016b). With a volumetric flow rate of 0.019 $m^3 s^{-1}$, they sample PM on glass fibre filters (Millipore, USA) positioned approximately 1.5 m above the ground level. Gravimetric analysis was used to determine the PM's mass. The filter was weighed before and after collection on an analytical balance (Mettler E., Zürich, Switzerland, ±0.0001 g) (NBR 13412).

Multivariate analysis techniques were used to verify the atmospheric behaviour in the downtown area, namely a hierarchical clusters analysis (HCA), which uses the Ward method with scaled distances, and a correlation matrix, which uses hourly data for meteorological variables like precipitation (Prec), pressure (P), relative humidity (RH), temperature (T), solar radiation (SR), wind direction (WD), and wind speed (WS), together with air pollutant data for PM_{10}, SO_2, O_3, and CO monitored at the Carioca station in 2013 and 2017. All statistical analyses were performed using the Statistical Computing Platform "R" (R Development Core Team, 2017).

3 RESULTS

3.1 VEHICULAR EMISSIONS

Pollutant levels of CO, NO_x, PM_{10} (kg), and GHG (CH_4 and CO_2) emitted by circulating buses in downtown Rio de Janeiro, before (2013) and after (2017) the urban mobility reorganization were measured using the methods employed in the vehicle emissions inventory (Table 3).

Table 3 | Pollutant emissions (kg) in the main avenues in downtown Rio de Janeiro before (2013) and after (2017) mobility changes

Avenue/pollutant (kg)	*2013*					*2017*				
	CO	*NO_x*	*PM_{10}*	*CH_4*	*CO_2*	*CO*	*NO_x*	*PM_{10}*	*CH_4*	*CO_2*
Passos	262	1,316	10	29	626	294	1,479	11	33	704
Antônio Carlos	1,789	8,993	67	201	4,278	936	4,706	35	105	2,239
Rio Branco	1,135	5,704	43	128	2,714	1,160	5,829	44	131	2,773
1º de Março	90	454	3.4	10	216	67	335	2.5	7.5	159
Total	3,276	16,467	120	368	7,834	1,413	12,349	90	276	5,875
Contribution (%)	12	59	0.4	1.3	28	7.1	62	0.4	1.4	29

Source: Authors

Bus emissions were dominated by nitrogen oxides (NO_x), which accounted for 59-62% of the total emissions, followed by carbon dioxide (CO_2), a greenhouse gas, which accounted for 28-29%. PM_{10}, CH_4, and CO accounted for 0.4%, 1.3-1.4%, and 7.1-12% of the total emissions, respectively. CO is a pollutant associated with light-duty cars, whereas NOx is the primary indicator of heavy-duty vehicles.

3.2 ENERGY CONSUMPTION

In May 2013, the total distance travelled by buses in scenario 1 was 2,417,970 km, while in scenario 2, it was 2,224,896 km (Table 4). The restructuring of traffic resulted approximated in an 8% reduction such in the distance travelled by buses downtown as in a reduced fuel consumption in 2017 compared to 2013. The estimated vehicle fuel consumption was 0.39 L km^{-1}, with no variation between 2013 and 2017.

Table 4 | Useful energy consumption, in MJ, in scenario 1 (May 2013) and scenario 2 (May 2017)

Fuel	*May 2013*		*May 2017*	
	Mineral Diesel	*Biodiesel*	*Mineral Diesel*	*Biodiesel*
Consumption (L)	895,858	47,150	798,293	69,417
Energy densities (MJ L^{-1})	35.5058	33.1610	35.5058	33.1610
Useful energy consumption (MJ)	31,808,109	1,563,557	28,343,985	2,301,931
Total useful energy consumption (MJ)	33,371,666		30,645,916	
Total distance travelled (km)	2,417,970		2,224,896	
Total commercial diesel (L)	943,008		867,710	

Note: Energy densities: 0.848 toe-m^{-3} for mineral diesel and 0.792 toe-m^{-3} for biodiesel (MMA, 2013).

Source: Authors

3.3 AIR QUALITY ASSESSMENT

Data from the monitoring sites were compared to the Brazilian Ambient Air Quality Standards (BAAQS) established by Conama Resolution No. 491/2018 (CONAMA, 2018), which came 28 years after the initial resolution (Conama 03/90). For Carioca and Castelo stations, Tables 5 and 6 show the maximum yearly concentrations from 2013 to 2017, indicating short-term exposure and annual mean concentrations representing long-term exposure.

PM_{10} concentrations in the downtown zone were the lowest over the research period at both sites in 2017, with a decrease in both long- and short-term exposures. PM_{10} mean concentrations fell from 12% and 25% between 2013 and 2017, respectively. High PM_{10} concentrations were reported in 2015, linked to increased infrastructure construction in the downtown area. In addition, in 2015 (48 µg m^{-3}) and 2016 (42 µg m^{-3}) of PM_{10}, long-term exposure values beyond the BAAQS limits were detected. In 2016, a decrease in PM_{10} concentrations was observed in response to the urban mobility reorganization.

Table 5 | Long-term (annual mean concentrations) and short-term (maximum annual concentrations) analysis for all pollutants monitored at the Carioca station from 2013 to 2017

Pollutant	*Year*	*N*	*Long-term exposure*				*Short-term exposure*			
			C_{mean}	*BAAQS*	*ΔC_{mean}¹ (%)*	*ΔC_{mean}² (%)*	*$C_{máx.}$*	*BAAQS*	*ΔC_{max}¹ (%)*	*ΔC_{max}² (%)*
PM_{10} 24h (µg m^{-3})	2013	353	33	40	-	-	104	120	-	-
	2014	324	35	40	6.2	6.2	88	120	-16.0	-16.0
	2015	360	35	40	6.2	-0.5	106	120	1.1	20.4
	2016	354	30	40	-8.3	-13.3	102	120	-2.2	-3.3
	2017	345	29	40	-13.6	-5.8	78	120	-23.5	-21.7
CO 8 h (daily maximum rolling average) (ppm)	2013	354	-	-	-	-	2.2	9	-	-
	2014	339	-	-	-	-	1.8	9	-18	-18
	2015	363	-	-	-	-	1.6	9	-24	-8
	2016	348	-	-	-	-	1.9	9	-10	19
	2017	355	-	-	-	-	1.8	9	-18	-9
O_3 8 h (daily maximum rolling average) (µg m^{-3})	2013	356	-	-	-	-	89	140	-	-
	2014	345	-	-	-	-	85	140	-4	-4
	2015	363	-	-	-	-	107	140	21	26
	2016	354	-	-	-	-	112	140	27	5
	2017	345	-	-	-	-	111	140	26	-1

Note:

Cmean – annual mean concentration

Cmax – annual maximum concentration

ΔCmean – mean concentration of one year in relation to some year

ΔCmax – maximum concentration of one year in relation to some year

1 – in relation to the concentration obtained in 2013

2 – in relation to the concentration obtained in previous year

Source: Adapted from Seconserma (2018) and Inea (2018).

Table 6 | Long-term (annual mean concentrations) and short-term (maximum annual concentrations) analysis for all pollutants monitored at the Castelo station from 2013 to 2017

Pollutant	Year	N	Long-term exposure				Short-term exposure			
			C_{mean}	BAAQS	ΔC_{mean}[1] (%)	ΔC_{mean}[2] (%)	$C_{máx.}$	BAAQS	ΔC_{max}[1] (%)	ΔC_{max}[2] (%)
PM_{10} 24 h (µg m^{-3})	2013	55	40	40	-	-	108	120	-	-
	2014	52	40	40	-1.4	-1.4	95	120	-12.0	-12.0
	2015	44	48	40	19.3	21.0	119	120	10.2	25.3
	2016	36	42	40	1.8	-14.6	69	120	-36.1	-42.0
	2017	42	34	40	-17.2	-18.7	85	120	-21.3	-23.2
$PM_{2.5}$ 24 h (µg m^{-3})	2013	58	18	20	-	-	58	60	-	-
	2014	52	16	20	-10.3	-10.3	36	60	-37.9	-37.9
	2015	40	17	20	-10.0	0.3	30	60	-48.3	-16.7
	2016	48	16	20	-16.4	-7.1	40	60	-31.0	33.3
	2017	36	12	20	-37.6	-25.4	32	60	-44.8	-20.0

Note:

Cmean – annual mean concentration

Cmax – annual maximum concentration

ΔCmean – mean concentration of one year in relation to some year

ΔCmax – maximum concentration of one year in relation to some year

1 – in relation to the concentration obtained in 2013

2 – in relation to the concentration obtained in previous year

Source: Adapted from Seconserma (2018) and Inea (2018).

$PM_{2.5}$ concentrations in 2017 were compared to previous years. Furthermore, none of the recorded values was higher than the BAAQS for short-term exposure at the Carioca station during any monitored years. According to Table 6, there was a 38% reduction in yearly $PM_{2.5}$ mean concentrations before (2013) and after (2017) the reorganization of urban transportation.

The highest CO values were recorded between 18:30 and 20:30. This interval reflects peak transit times when people leave work, and traffic bottlenecks occur daily. CO is a contaminant emitted by automobiles circulating in the area due to the incomplete combustion of fossil fuels. The mean concentration (8 h) was five times lower than the BAAQS (9 ppm). Ozone was the only pollutant that showed 8-hour average concentrations greater in 2015, 2016, and 2017 compared to 2013. Furthermore, a declining trend was not seen during the monitored period, and the levels of O_3 were above the BAAQS. To further understand this trend, researchers are tracking VOCs and NO_x, precursors of O_3 in the atmosphere, via photochemical reactions (ARBILLA *et al.*, 2002; ATIKINSON, 2000). However, both pollutants were not monitored in the Carioca station.

Hierarchical cluster analysis (HCA) was performed on all meteorological variables and pollutants monitored at the Carioca station from 2013 to 2017 to examine the atmospheric behaviour in downtown Rio de Janeiro. The analysis demonstrated a high degree of similarity between air pollutants (PM_{10}, O_3, SO_2, and CO) and meteorological variables that dictate how local atmospheric dispersion occurs (Figure 2). PM_{10}, RH, WD, and solar radiation (SR) were grouped together. Some researchers have already looked into the impacts of the PM-SR correlation because black carbon is present in PM, absorbing solar radiation (GODOY *et al.*, 2009; VENTURA *et al.*, 2017, 2019b). However, no correlation was found between pressure and any of the variables evaluated.

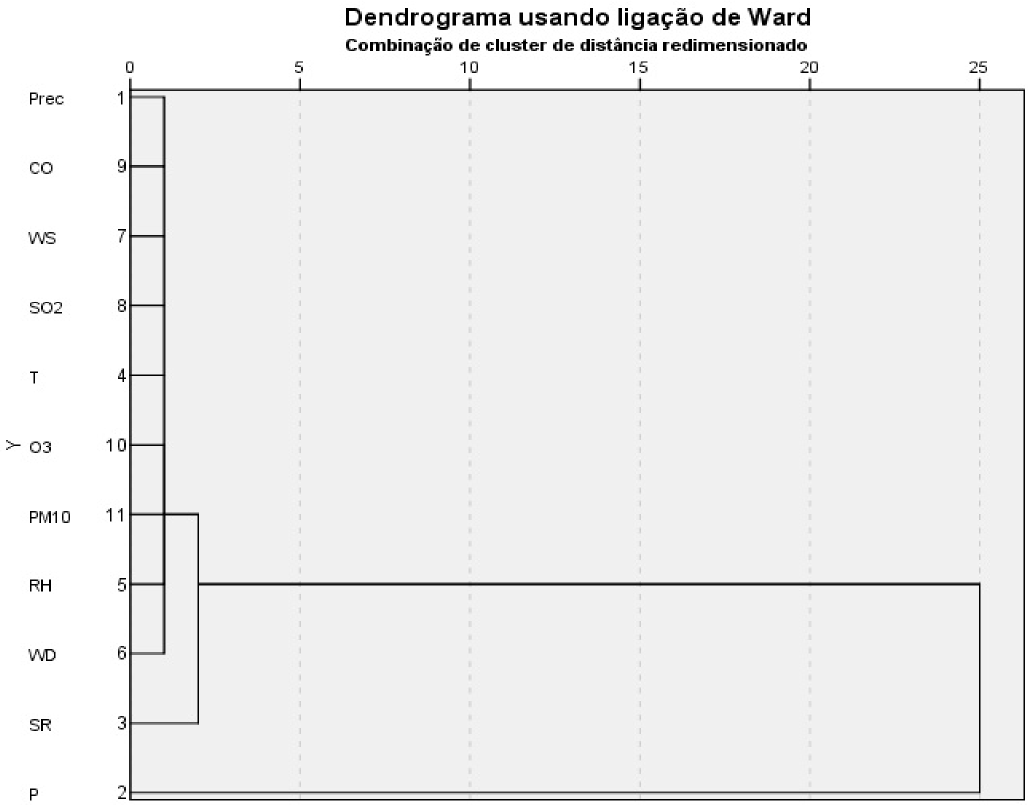

Figure 2 | Dendrogram of meteorological variables and pollutants monitored at the Carioca station from 2013 to 2017

Source: Authors

Precipitation did not show correlations with any other variable. The precipitation is the result of all meteorological variables working together. O_3 had a positive connection with T, SR, and RH, as expected. This pollutant is produced by photochemical processes and in the presence of SR, which has a strong relationship with temperature (0.70). Furthermore, both T and SR were associated with RH (-0.55 and -0.77), as seen in prior research focusing on Rio de Janeiro (VENTURA *et al*., 2017, 2019b). Ozone also had a weak relationship with wind variables (-0.31 and 0.46) owing to its low density, which allows it to be transported to and from different places depending on WD and WS. The multivariate study highlights that higher O_3 levels are more likely to occur on days with low RH and sunny days with high temperatures.

PM_{10} from vehicular emissions showed a moderate connection with CO (r = 0.53). It should be noted that these contaminants are not affected by weather conditions. As a result, the decrease in these atmospheric pollutants is more likely related to traffic than meteorological fluctuations.

4 DISCUSSION

Reduced urban bus lines, restrictions on light vehicles, changes in road infrastructure, and the implementation of LRVs, cable cars, and bike paths were all part of the urban mobility plan designed for the downtown region of Rio de Janeiro to host the 2014 Fifa World Cup FIFA and the 2016 Olympic Games. The works took place from September 2011 to June 2016. Based on this traffic restructuring, buses covered shorter routes, used less fuel, and produced fewer emissions, improving air quality. Compared to 2013, the pollutants generated by buses on the main roadways in the downtown area decreased by 25% in 2017. Antônio Carlos Avenue showed the most significant drop (48%), followed by 1° de Março Ave (26%). This was due to the improvement of bus routes and the opening of a new tunnel and the Via expressway. However, in Passos Ave. there was a 12 % increase in emissions because most of the buses started to circulate after Rio LTVs operation (2017). There was no significant change in the characteristics of the vehicular flow in Rio Branco Ave. because only changes in light-duty vehicles transit occurred, whereas buses kept circulating at nearly the same rate. This means 7,000 kg of pollutants, such as GHGs, are no longer discharged into the atmosphere each month. The energy consumption estimation revealed that the reorganization in urban mobility, driven by the reduction of circulating bus lines in the region, resulted in an 8% reduction in the distance travelled by buses in this area. Biodiesel consumption by buses increased by 47% from 2013 to 2017, while mineral diesel consumption decreased. This is primarily due to the Brazilian government's increasing biodiesel percentage in commercial fuel from 5% in 2013 to 8% in 2017.

The air quality in downtown Rio de Janeiro improved in response to urban transportation optimization activities, infrastructure improvements performed in 2016, and modifications in the fuel mix. The annual mean concentrations of particulate matter (PM_{10} and $PM_{2.5}$) decreased by 38% between 2013 and 2017, while CO maximum concentrations decreased by 18%. These findings matched those seen in other places, such as Toronto, Canada. After reorganizing their urban transportation, Paris, France, and Beijing, China, will host major sporting events such as the World Cup and the Olympic Games (BIGAZZI; ROULEAU, 2017; CHAKHTOURA; POJANI, 2016; GUO *et al.*, 2013; LI *et al.*, 2011).

Ozone concentrations, however, increased but did not surpass the national limits. Because intricate photochemical reactions create this pollutant, it is not easy to manage. Rio de Janeiro has a history of high ozone levels. Increased O_3 concentrations were evaluated in research conducted during the partial shutdown due to COVID-19 when there was a significant drop in car traffic (DANTAS *et al.*, 2020). The authors found that as NO_x levels fell, O_3 levels rose. The increase in O_3 levels was ascribed in another study to high ratios of NO_x/NO in various Rio de Janeiro islands (GIODA *et al.*, 2018). Ozone levels were also much higher during and after the Olympic season when traffic was reduced and managed (DE LA CRUZ *et al.*, 2019). NO_x levels, on the other hand, were lower, indicating a direct involvement in O_3 production. NO_x and O_3 were not observed at the sites we investigated, but the calculated NO_x emissions suggested a 25% reduction. This could be a sign of increased O_3 formation.

5 CONCLUSIONS

Vehicle emissions are the primary source of pollutants in many large cities. This study found that a well-executed plan to improve urban mobility, such as in Rio de Janeiro's downtown region, with reductions in urban bus lines, restrictions on light vehicles, changes in road infrastructure, and the implementation of LRVs, resulted in environmental benefits, particularly for the local environment. Between 2013 and 2017, a reduction of 8% in energy consumption by buses resulted in a reduction of up to 25% in GHG emissions. In addition, the air quality in the downtown zone improved by 14 –45% in terms of major pollutants (PM_{10}, $PM_{2.5}$, and CO). On the other hand, secondary pollutants (O_3) increased in response to weather conditions and reduced VOC_s and NO_x levels. It is concluded that proper traffic management methods and urban mobility enhancements can assist in limiting the consequences of emissions, air pollution concentrations, human exposure, and environmental impacts.

The lack of monitoring data is one of the limitations of this work. Nonetheless, the results were valuable because they demonstrated that clever measures could produce excellent results. Traffic management, which includes real-time volume, speed, and categorization monitoring, allows for in-depth and extensive research. From our perspective, the best way to construct an urban mobility plan is for key stakeholders (*i.e.*, Municipal Authorities, Public Administration, Environmental Agencies, Transport Authorities, etc.) to collaborate on policies and strategies to achieve beneficial outcomes for the region.

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