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RESEARCH

Is the expansion of the subway network alone capable of improving local air quality? A study case in São Paulo, Brazil

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Abstract One of the policies adopted to reduce vehicular emissions is subway network expansion. This work fitted interrupted regression models to investigate the effects of the inauguration of subway stations on the mean, trend, and seasonality of the NO, NO_2, NO_x, and PM_{10} local concentrations. The regions investigated in the city of São Paulo (Brazil) were Pinheiros, Butantã, and St. Amaro. In Pinheiros, after the inauguration of the subway station, there were downward trends for all pollutants. However, these trends were not significantly different from the trends observed before. In Butantã, only regarding NO, there was a significant reduction and seasonal change after the subway station's inauguration. In St. Amaro, no trend in the PM_{10} concentration was noted. The absence of other transportation and land use policies in an integrative way to the subway network expansion may be responsible for the low air quality improvement. This study highlights that the expansion of the subway network must be integrated with other policies to improve local air quality.

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Introduction

Air pollution is responsible for 7.6% of all deaths around the world and is the fifth leading risk factor (Cohen et al., 2017). The elevated concentrations of air pollutants in large urban centers, such as particulate matter (PM) and nitrogen oxides (NO_x), have already been related to different types of cancer (Deng et al., 2016; Gharibvand et al., 2017; Vena, 1982), miscarriage, premature birth and low-weight at birth (Lavigne et al., 2018; Stieb et al., 2016), metabolic disturbances (such as diabetes) (Bowe et al., 2018), and neurologic disturbances (such as Parkinson, Alzheimer, and low performance in cognitive tests) (Cacciottolo et al., 2017; Chen et al., 2018; Jia et al., 2018; Ritz et al., 2016).

São Paulo is the largest Brazilian city and one of the largest urban centers in the world. The most recent estimate is that the city has 12.3 million inhabitants, and, in 2018, there were 8.3 million vehicles (IBGE, 2018, 2020). As in other urban centers around the world, vehicles are the main responsible for air pollution in São Paulo (CETESB, 2019b). In the last 30 years, the governments of Brazil and São Paulo state have been applying several measures to reduce pollution such as the Brazilian Motor Vehicle Air Pollution Control Program (PROCONVE, in

Portuguese), the no-drive days, and restrictions on heavy-weight vehicles' mobility in some avenues. Despite these policies, the air quality in the city is still worse than the World Health Organization (WHO) recommendations, and it is responsible for more than five thousand deaths every year (Abe & Miraglia, 2016).

The recent literature has been arguing that the key policy to reduce car use, and consequently vehicular emissions, is to provide alternatives so its use becomes unnecessary (Banister, 2008). In this sense, the encouragements of active transportation and railway transportation are essential measures toward more sustainable cities. In practice, however, these measures are often taken in a poorly integrated way, which can compromise the desired results.

One of the measures implemented in the city of São Paulo to reduce vehicle emissions was vehicular inspection. The program started in 2008 and was suspended in 2013. Araujo and Araujo (2020), using time series analysis techniques, evaluated the impacts of the implementation and suspension of the mandatory vehicle inspection in the city of São Paulo on morbidity and mortality related to air pollution. They concluded that there is no evidence that the program had a measurable positive impact on morbidity and mortality due to respiratory and circulatory diseases. The authors attributed the failure of the program to the increase in the number of vehicles (government incentives for vehicle purchase) and to the fact that only 3% of the inspected vehicles were reproved in the inspection.

Even in a poorly integrated way with other policies, some adopted measures showed positive environmental and health effects. This is the case of the implementation of PROCONVE. Several studies conducted in Brazil and especially in São Paulo indicated a decline in concentrations of atmospheric pollutants, even with an increase in the vehicle fleet, in addition to a decrease in cardiovascular mortality and a stabilization of the mortality rate due to chronic obstructive pulmonary disease (Abe & Miraglia, 2018; Escuciatto et al., 2016; Pérez-Martínez et al., 2015). Despite this success, Leirião and Miraglia (2019) emphasize that the program should be complemented by a vehicle retirement program to accelerate the replacement of the most polluting vehicles with more modern ones.

The evaluation of environmental programs is fundamental to assist in the decision-making process regarding the improvement and adoption of new public policies. In the last decades, the statistical literature on air quality has increased, and special attention has been given to pollutant concentrations and human exposure (Maranzano et al., 2020). In this context, the time series analysis is an important tool that makes it possible to predict, measure, and fit models that describe the behavior of the series before and after the implementation of a policy, program, or intervention, allowing to measure its effectiveness (Briët et al., 2013).

Fig. 1 Map of the study area. The red circles represent the air quality monitoring stations, and the crosses represent the subway stations. The blue circles indicate the three regions of air quality monitoring station + subway station (1, 2, and 3) that were identified to perform this study analysis. Source: elaborated by the authors based on CETESB (2018) and Prefeitura de São Paulo (2017)

Given the importance of time series analysis to evaluate the effectiveness of environmental and health policies, this study aimed to evaluate one of the most expensive and widespread measures in the world to reduce vehicular emissions: the expansion of the subway network. To evaluate the effects of the inauguration of subway stations on the local air quality, we fitted interrupted regression models for several daily mean pollutant concentrations in São Paulo. So, the main goal of this work was to measure the impact of the opening of subway stations on the local concentration of some pollutants. The impacts were evaluated as changes in the mean, trend, and seasonality of pollutant concentrations.

Material and methods

Study area

In São Paulo, the air quality is monitored by the environmental agency of the São Paulo state (Companhia Ambiental do Estado de São Paulo— CETESB, in Portuguese), and the monitoring network is constituted of 19 stations that are heterogeneously distributed across the city (Fig. 1). Some of these stations are operating since the 1970s, so they have been registering the pollutants concentrations before and after the opening of the majority of the subway stations in the city. Using the QGIS 3.10.11 software, we identified all the monitoring stations that are localized less

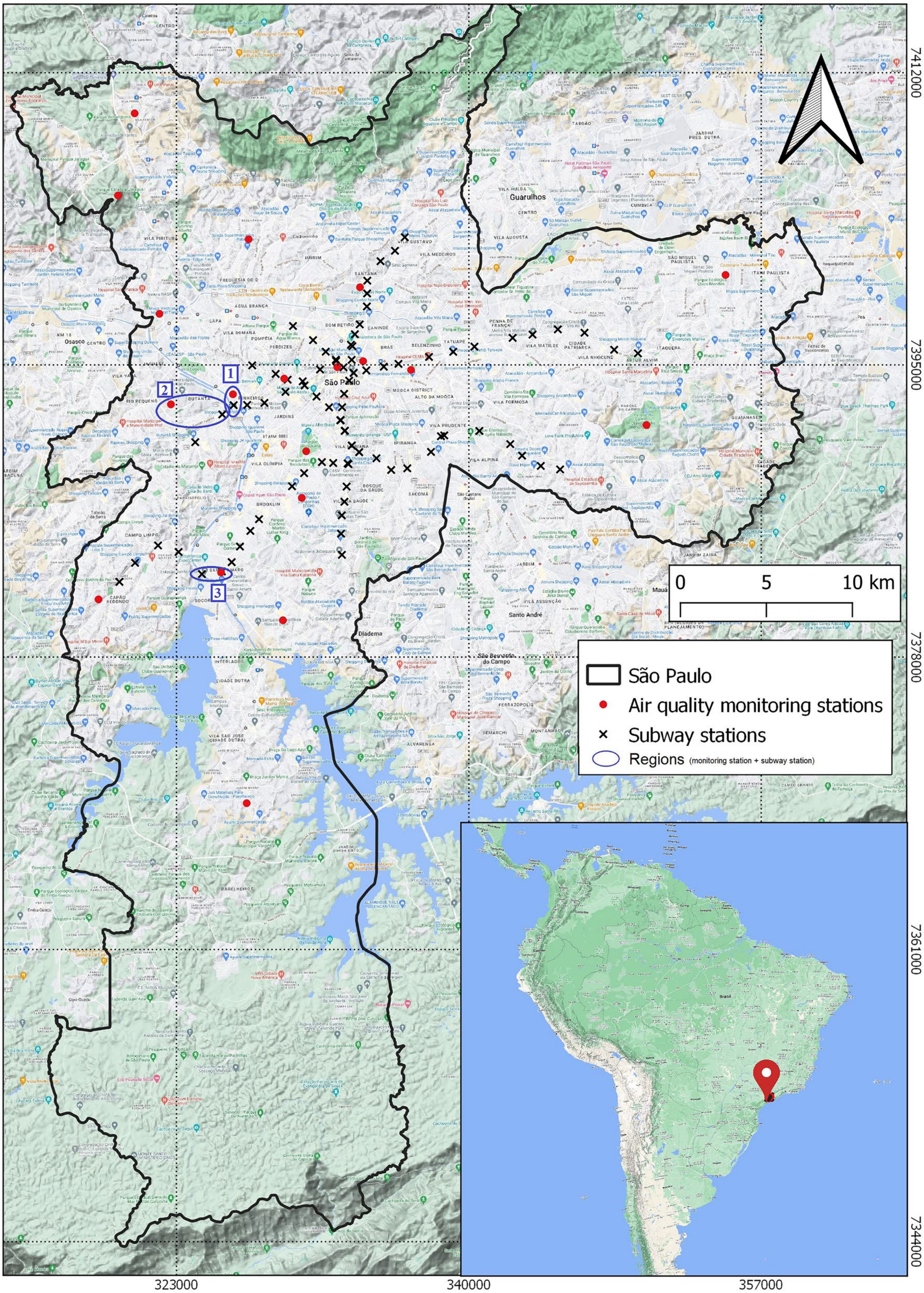
7412000
7395000
7378000
7361000
7344000
323000
340000
357000
0
5
10 km
São Paulo
Air quality monitoring stations
Subway stations
Regions (monitoring station + subway station)
1
2
3

Table 1 The three pairs of "air quality monitoring station + subway station" identified to perform this study analysis

Region	Air quality monitoring station	Subway station	Distance between the stations (m)	Date of the subway station inauguration	Analyzed pollutants	Air pollution time series
1	Pinheiros	Pinheiros	640	5/16/2011	NO, NO_2, NO_x	1/1/2006 - 12/31/2019
2	Cidade Universitária	Butantã	3000	3/28/2011	NO, NO_2, NO_x	1/1/2007 - 12/31/2018
3	Santo Amaro	Santo Amaro	950	10/20/2002	PM_{10}	1/1/1998 - 12/31/2019

than 3 km from a subway station; it originated "monitoring station–subway station" pairs. The maximum distance criterion of 3 km was defined based on the representativeness of the São Paulo air quality monitoring stations. According to CETESB, the majority of the stations have a 4 km of representativeness (CETESB, 2016). The selection criteria for the pairs "monitoring station–subway station" to be investigated was the availability of local air quality data covering at least 5 years before and 5 years after the opening of the subway station. These criteria resulted in three "monitoring station–subway station" regions (Table 1; Fig. 1).

The Butantã subway station is closer to the Pinheiros air quality monitoring station than to the one at Cidade Universitária (Fig. 1). Nevertheless, the Butantã and the Pinheiros subway stations were inaugurated 48 days apart; hence, if Pinheiros' air quality monitoring station was considered as a reference for both, the results would be equivalent. Besides, the concentration of pollutants measured in the Pinheiros monitoring station is strongly influenced by the presence of a heavy-traffic road located less than 100 m from the station. The traffic on this road is not affected by the existence of the new subway station (see more in the "Results and discussion" section). So, in order to provide a different analysis, the Cidade Universitária monitoring station was paired with the Butantã subway station. The pairing also respects the criteria of less than 3 km distance.

Data source and processing

The hourly air quality data was downloaded from the CETESB online system (Sistema de Informações da Qualidade do Ar – QUALAR, in Portuguese). The selected pollutants were nitrogen oxides (NO_x), nitrogen monoxide (NO), nitrogen dioxide (NO_2), and particulate matter with less than 10 μm (PM_{10}). These are the pollutants that are frequently related to vehicular emissions, and they were measured at least 5 years before and after the paired subway station inauguration. The available pollutant data for each region is presented in Table 1.

Based on the hourly pollutant concentrations, the daily means were calculated. Only days with at least eighteen hourly measures were considered in the statistical analyses.

Statistical analyses

The generalized autoregressive and moving average (GARMA) model, proposed by Benjamin et al. (2003), combines the flexibility of the generalized linear models (McCullagh & Nelder, 1989) and the autoregressive and moving average models (Box et al., 1970), which are appropriate to consider the autocorrelation of time series.

As the time series of daily pollutant concentrations assume only non-negative values, then the Gamma distribution seems an appropriate distribution for the pollutants. After plotting all time series, it is relevant to include trend and seasonality terms and the subway effect, assuming that it may affect not only the pollutant intercept but also the trend and the seasonality after the opening of each subway station. The model also considered weekday and holiday effects. As the pollutant mean is always non-negative, we considered the logarithm of the mean (μ_t) as the linear predictor associated with the observed pollutant, y_t, at day t, assuming for a generalized autoregressive and moving average with 2 autoregressive components, called GARMA(2,0), with

$$X_t\beta = \beta_0 + \beta_1(t - t_0) + \beta_2\cos(2\pi t/365) + \beta_3 sin(2\pi t/365) + \beta_4\cos(2\pi t/365) + \beta_5 sin(2\pi 2t/365) + \beta_6 Saturday_t + \beta_7 Sunday_t + \beta_8 Holiday_t + \beta_9 Holiday2_t + \beta_{10} Subway_t + \beta_{11} Subway_t(t - t_0) + \beta_{12} cos(2\pi t/365) + \beta_{13} Subway_t sin(2\pi t/365)$$

$$\ln(\mu_t) = X_t\beta + \varphi_1[\ln(y_{t-1}) - X_{t-1}\beta] + [\ln(y_{t-2}) - X_{t-2}\beta],$$

where $t = 1, 2, \ldots, T$, T is the number of days of the observed pollutant time series; t_0 is the time t corresponding to the opening of the subway station; μ_t is the mean of the pollutant at time t; Holiday_t is an indicator variable equal to 1 if the t-day is holiday and 0 otherwise; Holiday2_t is equal to 1 if t occurs on Monday and the holiday is on Tuesday or if t occurs on Thursday and there is a holiday on Friday; and Subway_t is an indicator variable equal to 0 before the opening of the subway station and 1 after the opening. The functions $\sin(2\pi t/365)$ and $\cos(2\pi t/365)$ model the seasonality that presents a cycle of 365 days.

The parameter β_1 is associated with the trend effect before the station opening and $(\exp(365\,\beta_1) - 1)100$ corresponds to the annual percentage change of the mean pollutant concentration. The parameter β_{10} measures the shift in the mean concentration after the subway opening, and the trend change is measured by β_{11}. Also, the seasonality may change after the opening if β_{13} is significant. The subway effects were estimated as the percentage change after the opening and the annual percentage change after each station opening. The parameters β_2 and β_5 correspond to the seasonality effects before the subway opening and β_6 to β_{10} correspond, respectively, to the effects of each day being Saturday, Sunday, a holiday, or a holiday that is established when there is a holiday on Tuesday or Thursday.

The model was fitted using the maximum likelihood estimation method using the library gamlss.

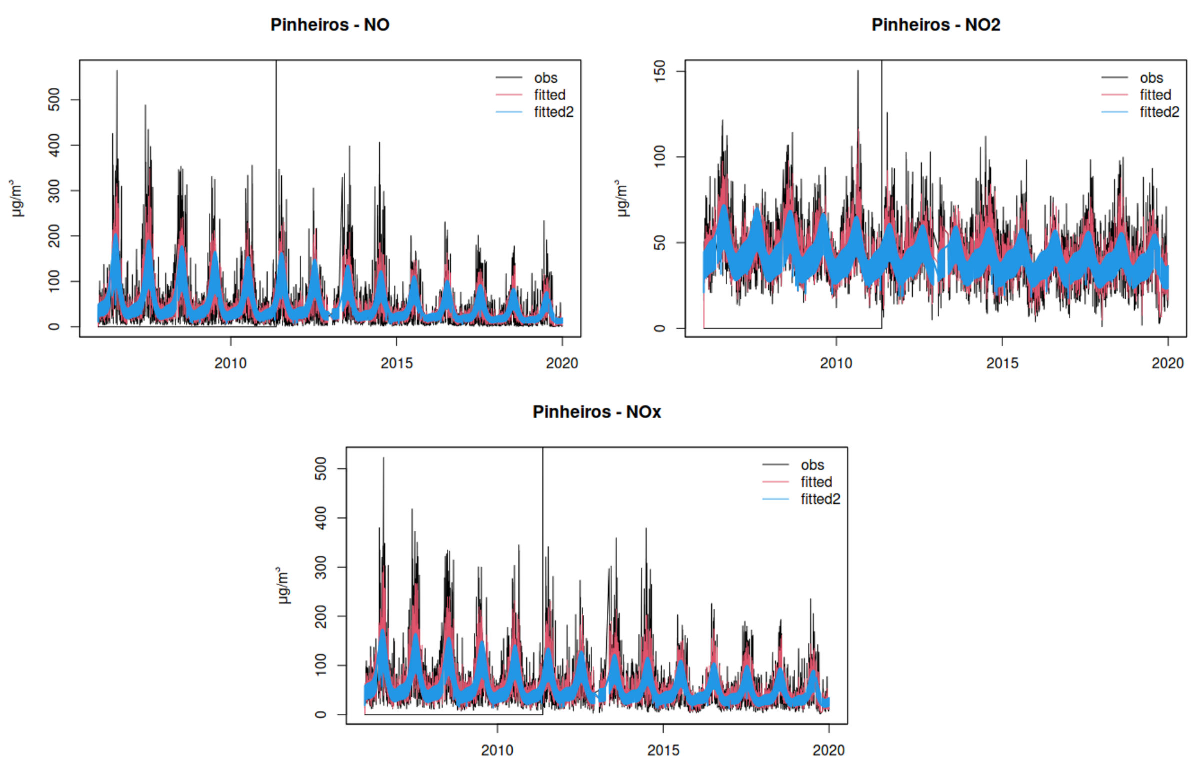

Fig. 2 NO, NO_2, and NO_x daily mean concentration between 2006 and 2019 in the region of Pinheiros subway station. The vertical bars on the three graphs indicate the inauguration of the Pinheiros subway station (5/16/2011)

Table 2 Estimated effects, 95% confidence intervals, and *p*-values for each pollutant — Pinheiros. Annual % indicates the trend before the subway; Cos (2pi t/365), Sin (2pi t/365), Cos (2pi 2t/365), and Sin (2pi 2t/365) indicate the seasonality before the subway; Saturday %, Sunday %, Holiday %, and Holiday 2% indicate the effects of weekends and holidays; Subway% indicates the immediate effect after the subway; Sub. Annual% indicates the trend after the subway; and Sub. Cos and Sub. Sin indicate the seasonality after the subway

	NO				NO_2				NO_x			
	Est	95% CI		*p*	Est	95% CI		*p*	Est	95% CI		*p*
Intercept	56.0	49.9	62.9	**< 0.001**	48.6	45.0	52.6	**< 0.001**	66.2	59.6	73.5	**< 0.001**
Annual %	−6.8	−10.2	−3.4	**< 0.001**	−2.4	−4.9	0.1	**0.058**	−4.9	−8.1	−1.7	**0.003**
Cos (2pi t/365)	1.7	1.5	1.8	**< 0.001**	1.1	1.0	1.1	**0.004**	1.4	1.3	1.5	**< 0.001**
Sin (2pi t/365)	1.7	1.6	1.8	< 0.001	1.2	1.2	1.3	**< 0.001**	1.5	1.4	1.6	< 0.001
Cos (2pi 2 t/365)	0.9	0.8	0.9	**< 0.001**	0.9	0.9	1.0	< 0.001	0.9	0.8	0.9	**< 0.001**
Sin (2pi 2 t/365)	1.2	1.2	1.3	**< 0.001**	1.0	0.9	1.0	**0.335**	1.2	1.1	1.2	**< 0.001**
Saturday %	−27.0	−31.1	−22.7	**< 0.001**	−15.4	−17.6	−13.1	**< 0.001**	−21.6	−25.1	−18.0	**< 0.001**
Sunday %	−54.7	−57.2	−52.0	**< 0.001**	−35.5	−37.2	−33.7	**< 0.001**	−47.8	−50.2	−45.4	**< 0.001**
Holiday %	−47.4	−52.1	−42.2	**< 0.001**	−27.3	−30.6	−23.9	**< 0.001**	−36.4	−40.9	−31.6	**< 0.001**
Holiday2%	−18.1	−30.0	−4.2	**0.013**	−8.8	−15.5	−1.6	**0.017**	−19.6	−28.7	−9.3	**< 0.001**
Subway%	19.9	3.5	39.0	**0.016**	0.7	−9.0	11.3	0.898	8.9	−5.1	24.9	0.224
Sub. Annual %	−2.3	−6.3	1.8	0.263	1.2	−1.7	4.1	0.426	−0.1	−3.7	3.7	0.972
Sub. Cos	0.9	0.8	1.0	0.071	1.0	0.9	1.1	0.827	1.0	0.9	1.0	0.319
Sub. Sin	1.0	0.9	1.1	0.959	0.9	0.9	1.0	0.136	0.9	0.9	1.0	0.211

Bold values indicates statistical significance (*p*-value < 0.05)

util in the statistical software R. The order of the model was chosen equal to 2 to eliminate any residual autocorrelation. The residual autocorrelation plot was analyzed to evaluate the null residual autocorrelation.

Results and discussion

Region 1: Pinheiros

The NO, NO_2, and NO_x atmospheric concentrations presented seasonal behavior, with higher concentrations during the dry winter season — between May and September (Fig. 2). This behavior is well-known in São Paulo and is described for several pollutants (CETESB, 2019b). On weekends, the concentration of the three pollutants decreased, mainly on Sundays, whose reduction rates achieved 54.7% for NO, 35.5% for NO_2, and 47.8% for NO_x (see % Sunday in Table 2), which was expected, since it is well described in the literature that changes in pollutant emissions during the weekday and weekends are associated with changes in traffic dynamics (Beirle et al., 2003; Morawska et al., 2002; Riga-Karandinos & Saitanis, 2005). The same decreased behavior can be observed on holidays, being the NO reduction concentration the highest observed.

Before the inauguration of the Pinheiros subway station, there was already a general trend of decrease for the three pollutants: −6.8% per year for NO, −2.4% for NO_2, and −4.9% for NO_x (see Annual% in Table 2). After the subway inauguration, there was no significant change in this trend (see Sub. Annual% in Table 2). The subway inauguration also did not affect the seasonal behavior of the pollutants (see Sub. Cos and Sub. Sin in Table 2). Right after the inauguration, there was a 20% increase in NO concentration (Subway% in Table 2, $p = 0{,}016$). For NO_2 and NO_x pollutants, there was no significant change in their concentrations right after the subway inauguration (Subway% in Table 2).

Despite the annual trend for the pollutant concentrations that have remained the same after the inauguration of the subway station, there is some evidence that this intervention changed the transport dynamics in the region. For instance, between 2008 and 2019, the São Paulo Traffic Agency (Companhia de Engenharia de Tráfego — CET, in Portuguese) reported the vehicle traffic counting in a large road 650 m far from

Pinheiros subway station (Eusébio Matoso Avenue). Between 2008 and 2011, the sum of vehicles considering the morning and afternoon peaks was 36,379, 32,555, 42,768, and 44,364, respectively (CET, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020). After 2011, the average diminished continuously until it reached 31,264 vehicles in 2015 and grows again between 2016 and 2019, but without returning to the values prior to the inauguration of the subway station (CET, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020). This behavior of reduction in the circulation of vehicles occurred both for cars and for buses. While the number of vehicles declines, the number of passengers observed in the Pinheiros subway station increases. In 2011 (inauguration year), about 70 thousand passengers were counted in the station in a workday; in 2018, there were over 143 thousand (Via Quatro, 2020).

The 20% increase in NO concentration right after the inauguration may be a an indication that the location became a transportation hub, bringing people from other locations to the subway station. Regarding the lack of change in the air quality trend after the subway station inauguration, there is one important event that certainly affected the local air quality in the region and probably contributed to this result. Two years after the inauguration of the Pinheiros subway station, a bus terminal started to operate next to the station, and in São Paulo, buses are responsible for 12% of NO_x emissions (CETESB, 2019a). The Pinheiros bus terminal serves 41 bus lines and operates 24 h per day (SPTrans, 2020). So, even considering the above-mentioned decrease in the traffic resulting from the migration from car and buses to the subway, the emissions from the buses inside the terminal compromised the local air quality improvement. The vehicles counting revealed that there was a 18% decrease in the bus traffic and 7% decrease in the car traffic between 2011 and 2012 (CET, 2012, 2013). However, it is possible that, even considering that buses started to circulate in smaller numbers, the emissions arising from the constant departures of buses at the new terminal have compensated for a possible reduction

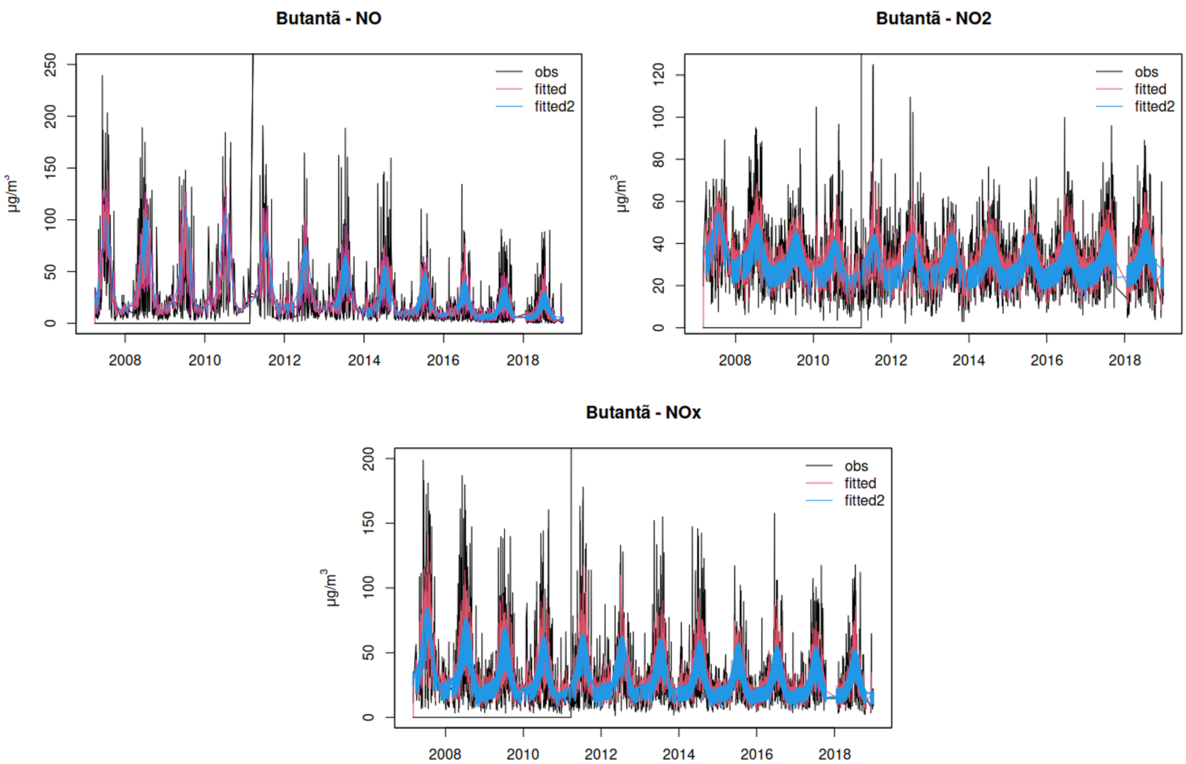

Fig. 3 NO, NO_2, and NO_x daily mean concentration between 2007 and 2019 in the region of Butantã subway station. The vertical bars on the three graphs indicate the inauguration of the Butantã subway station (3/28/2011)

Table 3 Estimated effects, 95% confidence intervals, and *p*-values for each pollutant — Butantã. Annual % indicates the trend before the subway; Cos (2pi t/365), Sin (2pi t/365), Cos (2pi 2t/365), and Sin (2pi 2t/365) indicate the seasonality before the subway; Saturday %, Sunday %, Holiday %, and Holiday2% indicate the effects of weekends and holidays; Subway% indicates the immediate effect after the subway; Sub. Annual% indicates the trend after the subway; and Sub. Cos and Sub. Sin indicate the seasonality after the subway

	NO				NO_2				NO_x			
	Est	95% CI		*p*	Est	95% CI		*p*	Est	95% CI		*p*
Intercept	31.7	24.6	40.8	**< 0.001**	29.5	27.0	32.1	**< 0.001**	28.8	25.6	32.5	**< 0.001**
Annual %	1.0	−8.8	11.8	0.847	−8.5	−11.9	−5.0	**< 0.001**	−9.4	−14.1	−4.6	**< 0.001**
Cos (2pi t/365)	0.9	0.8	1.1	0.499	0.9	0.9	1.0	0.054	0.9	0.9	1.0	0.147
Sin (2pi t/365)	2.6	2.3	3.0	**< 0.001**	1.2	1.2	1.3	**< 0.001**	1.7	1.6	1.9	**< 0.001**
Cos (2pi 2 t/365)	0.8	0.8	0.9	**< 0.001**	1.0	0.9	1.0	0.208	0.9	0.8	0.9	**< 0.001**
Sin (2pi 2 t/365)	0.8	0.8	0.9	**< 0.001**	0.9	0.9	1.0	**< 0.001**	0.9	0.8	0.9	**< 0.001**
Saturday %	−27.1	−34.1	−19.3	**< 0.001**	−18.0	−20.9	−14.9	**< 0.001**	−24.4	−28.2	−20.5	**< 0.001**
Sunday %	−54.8	−59.4	−49.7	**< 0.001**	−34.5	−36.9	−32.0	**< 0.001**	−46.1	−48.8	−43.2	**< 0.001**
Holiday %	−39.9	−51.0	−26.2	**< 0.001**	−26.4	−30.9	−21.6	**< 0.001**	−32.0	−37.9	−25.6	**< 0.001**
Holiday2%	5.3	−18.4	35.9	0.693	−8.2	−17.2	1.7	0.100	−15.2	−26.6	−2.1	**0.024**
Subway%	4.9	−21.0	39.3	0.741	12.0	0.9	24.4	**0.034**	19.5	3.2	38.3	**0.017**
Sub. Annual %	−14.6	−23.2	−5.1	**0.003**	10.0	5.7	14.5	**< 0.001**	7.2	1.4	13.3	**0.014**
Sub. Cos	0.9	1.1	0.4	0.331	1.0	0.9	1.1	0.840	1.0	0.9	1.1	0.849
Sub. Sin	0.8	1.1	0.1	**0.007**	1.0	0.9	1.1	0.926	0.9	0.8	1.0	0.156

Bold values indicates statistical significance (*p*-value < 0.05)

in emissions from vehicle traffic. It is well-known that more pollutants are emitted when the vehicles are started, and the older the vehicle, more pollutants are emitted (Nogueira et al., 2019). So, considering that, in São Paulo, more than 45% of the city buses are older than 10 years and diesel-fueled (CETESB, 2019a), it is important that policymakers must improve the public transportation system more comprehensively and with additional measures to ensure sustaining the benefits of the multimodal alternatives.

Region 2: Butantã

The seasonal behavior and the reductions in the concentration of pollutants on weekends and holidays described in Pinheiros are also present in Butantã (Fig. 3). The NO, NO_2, and NO_x concentrations measured in Butantã are lower than the concentrations registered in Pinheiros possibly because the monitoring station is located inside a university campus which presents a larger tree-covered area and it is less subjected to road traffic.

The time series analysis indicated that, before the subway inauguration in Butantã, there was a downward trend in the NO_2 (−8.5% per year) and NO_x (−9.4%) concentrations (see Annual % in Table 3). Regarding NO, no significant trend was observed in the same period. After the Butantã subway inauguration, the NO concentration trend was altered, and it was verified a –14.6% annual decrease (see Sub. Annual % in Table 3 and Fig. 3). This downward trend in the NO concentration was accompanied by an alteration in the seasonal behavior of this pollutant, which started to present lower concentration peaks during the winter (see Sub. Sin in Table 3 and Fig. 3). After the intervention, the level and trend in NO_2 and NO_x concentrations were also altered, but in these cases, the new trends revealed a significant deterioration in the air quality (see Subway % and Sub. Annual % in Table 3).

The distinct impacts on pollutant concentrations after the expansion of the railway system were also described in Changsha (China), Germany, and Delhi (India). In Changsha, after the opening of a new subway line, it was found a significant reduction in carbon monoxide (CO) concentration (18.1%), but there were no verified significant changes in particulate matter and ozone concentrations (Zheng et al., 2019). In Germany, a 10-year analysis showed that the rail service was able to promote a great decrease in NO concentration, but the effects on CO and NO_2 were weaker (Lalive et al., 2013). In Delhi, the first stretch of the Yellow Line resulted in a great reduction in CO concentration but not in NO_2 concentration. In its turn, the introduction of the Blue Line resulted in a 31% decrease in NO_2 concentration (Goel & Gupta, 2015).

Among the nitrogen oxides (NO_x), the NO is the one whose source is primarily the fossil fuel burn (Atkinson, 2000); possibly, for this reason, a greater concentration reduction of this pollutant was observed when compared to the others. The atmospheric NO_2 is usually formed from the combination of NO and ozone (O_3), in the chemical balance $NO + O_3 \leftrightarrow NO_2 + O_2$ (Atkinson, 2000). In this sense, the decreasing trend observed in the NO concentration after the subway station inauguration indicates that this intervention reduced vehicular emissions in the region. Another evidence of this reduction is that the decrease in the NO concentration was simultaneous with an increasing trend in the average number of passengers counted in the Butantã subway station (the number of passengers was about 24 thousand per workday in 2011 and increased to 70 thousand in 2018) (Via Quatro, 2020).

The levels of NO_2 observed in the atmosphere usually tend to decrease in the period of the day of greatest insolation and grow at the end of the day. The consumption of NO_2 by direct photochemical reactions generates O_3. The O_3 formation is promoted in environments with high voltaic organic compounds (VOCs) concentrations which is the case in the region since it has a large tree-covered area and consequently high biogenic emissions (Madronich, 2014). The increase in O_3 formation may explain the observed increase in the NO_2 concentration and decrease in NO concentration in the study area (Atkinson-palombo et al., 2006; Finlayson-Pitts & Pitts Jr, 1999; Souza et al., 2017).

In the region, the subway implementation also resulted in other changes that may have contributed to the NO concentration reduction. The first of them was the substitution of the old buses which performed transportation inside the university campus. They were replaced by new buses that incorporated the subway station in the itinerary. Even with the increase in the number of buses to perform this local transportation, technological improvement and the lower emission factor resulted in reduced NO emissions (Ferrarese at al., 2012). Besides that, after the subway station's inauguration, several bus lines that used to enter the campus started to have the subway station as the final stop. So, the bus traffic inside the campus and nearby the monitoring station became lower. In this sense, the results found in the Butantã region corroborates the statement made in relation to the Pinheiros region regarding the position of buses as the main responsible for emissions in these regions.

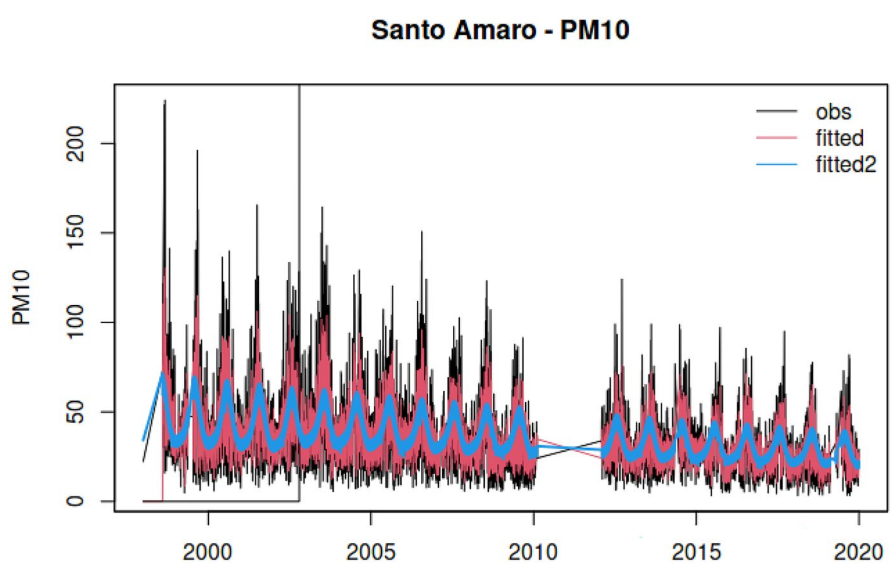

Fig. 4 PM_{10} daily mean concentration between 1998 and 2019 in the region of Santo Amaro subway station. The vertical bar indicates the inauguration of the Santo Amaro subway station (10/20/2002)

Table 4 Estimated effects, 95% confidence intervals, and p-values for PM_{10} pollutant — Santo Amaro. Annual % indicates the trend before the subway; Cos (2pi t/365), Sin (2pi t/365), Cos (2pi 2t/365), and Sin (2pi 2t/365) indicate the seasonality before the subway; Saturday %, Sunday %, Holiday %, and Holiday2% indicate the effects of weekends and holidays; Subway% indicates the immediate effect after the subway; Sub. Annual% indicates the trend after the subway; and Sub. Cos and Sub. Sin indicate the seasonality after the subway

	Santo Amaro — PM_{10}			
	Est	95% CI		p
Intercept	49.71	43.38	56.96	**< 0.001**
Annual %	−2.90	−7.13	1.52	0.195
Cos (2pi t/365)	0.74	0.68	0.80	**< 0.001**
Sin (2pi t/365)	0.88	0.81	0.94	**< 0.001**
Cos (2pi 2 t/365)	1.02	0.98	1.06	0.278
Sin (2pi 2 t/365)	1.06	1.02	1.10	**0.002**
Saturday %	−5.06	−8.12	−1.90	**0.002**
Sunday %	−16.53	−19.24	−13.72	**< 0.001**
Holiday %	−8.84	−13.64	−3.78	**< 0.001**
Holiday2%	−7.29	−15.36	1.56	0.104
Subway%	6.22	−9.06	24.08	0.446
Sub. Annual %	0.11	−4.28	4.70	0.961
Sub. Cos	1.04	0.95	1.14	0.362
Sub. Sin	1.04	0.96	1.13	0.327

Bold values indicates statistical significance (p-value < 0.05)

Region 3: St. Amaro

For the analysis of the impact of the subway station opening in region 3, there were no available data for NO, NO_2, and NO_x pollutants, but there were PM_{10} data. The recorded concentration of this pollutant also revealed a seasonal behavior mainly due to the difference in humidity and pluviosity between the winter and summer seasons (Fig. 4) (Sánchez-Ccoyllo & Andrade, 2002). As the Pinheiros region, the Santo Amaro monitoring station is located near one of the major roads of São Paulo (named Marginal Pinheiros) characterized by intense traffic, especially during rush time. Because of its location, Santo Amaro station is classified as a medium representativeness monitoring station, and its data represent accurately the air quality near the subway station which is located in the Marginal Pinheiros (CETESB, 2019b). Despite the lack of data between February 2010 and February 2012, the available data well fitted the model (Fig. 4).

In Fig. 4, the PM_{10} decreased concentration can be visually noted during the analyzed period. However, there was no significant trend between 1998 and 2018 (see Annual% and Sub. Annual% in Table 4). So, after the inauguration of the Santo Amaro subway station, the mean PM_{10} concentration remained as before (see Subway% and Sub. Annual% in Table 4). The subway station did not alter the seasonal behavior as well (see Sub. Cos and Sub. Sin in Table 4).

The Marginal Pinheiros, which is located the Santo Amaro subway station, connects the main avenues and roadways of São Paulo. Thus, the vehicles which pass through this road are primarily moving between the interior of the state and the port of Santos on the coast. As the existence of a subway station does not alter these travels, it is presumable that the vehicular emissions remained high even after the intervention. Although there was a relative concentration reduction on weekends and holidays for PM_{10}, the decrease was smaller than the other pollutants measured in the previous regions. This probably is a consequence of the intense traffic flow in the Marginal Pinheiros which is high even during the weekends and holidays (when people usually travel). The counting of vehicles, which has been performed since 2013 on this road, reveals that the traffic remains constant in recent years, oscillating between 15,600 and 16,600 considering the average of the two analyzed sites (CET, 2014, 2015, 2016, 2017, 2018, 2019, 2020). Since 2010, there is a restriction on trucks in Marginal Pinheiros, but there is no report about its effects on the local air quality. In a nearby avenue (Bandeirantes Avenue), this intervention was related to an improvement of 43% in PM_{10} concentration (Pérez-Martínez et al., 2017).

The number of passengers assisted by the Santo Amaro subway station is about 92 thousand per workday (Via mobilidade, 2020). According to the city zoning, the region is not residential and concentrates service, commerce, and industrial activities, so people who pass through this subway station are on work-related travel (Prefeitura de São Paulo, 2020). If there was no Santo Amaro subway Station, certainly these people would have to use buses or cars for commuting and the pollutant emissions would be even higher in the region.

Further discussions

Although the results were not a consensus about the local air quality improvement after the inauguration of a subway station, the positive impact of the subway's existence on the air quality on a larger scale had already been described in several regions, including the São Paulo municipality. Beijing (China) is an example of a city with similar issues to São Paulo. There, Li et al. (2019) investigated the possible relationship between subway station density and air quality and concluded that an increase in subway density by one standard deviation improves air quality by 2%. Despite the objective being similar to ours, it should be noted that the scale of analysis of their study was larger than the one used in this study. Here, the investigation focused on the change in air quality in the specific region where a subway station was opened. In addition, the extension of Beijing's subway network allows for the density analysis carried out by the researchers. There, the subway is more than 750 km long. In São Paulo, the length is just over 100 km. An investigation of the air quality impact of the subway expansion on a municipality scale had already been conducted in São Paulo using a different method. Comparing the air quality on regular days and during strike days which stopped the subway operation, it was possible to note that the mean PM_{10} concentration can be more than four times higher when the subway is not operating (da Silva et al., 2012). In the present study, the applied method focused on identifying correlations rather than establishing causality, so it was not possible to excluded the impact that all other measures may had on air quality. The implementation of a bus terminus next to the Pinheiros subway station, for example, turned the region into a transport hub. This, added to the intense truck traffic in the region, certainly has an adverse impact on air quality. Thus, this study raises an important argument to consider for future studies. Although on a larger scale the expansion of the subway network seems evident, on a local scale, it is necessary to consider more integrated mobility and environmental policies, especially to guarantee the health of people who spend long periods in transport hub areas.

The air quality in the regions of the Pinheiros (1) and Santo Amaro (3) are strongly influenced by the emissions from the vehicles which travel through Marginal Pinheiros. As this road is a central corridor that connects roadways and avenues, the subway stations are not enough to reduce the local traffic flow and the emissions remain high. The impact of emissions from trucks nearby the Pinheiros monitoring station has already been reported during a truck drivers' strike in 2018. During this strike, the NO_x concentration was 35% lower in the region (Leirião et al., 2020). In regions that are characterized by heavy traffic, such as Pinheiros (1) and Santo Amaro (3), policies to improve vehicle flow should be carefully designed to also consider air quality improvement. Instead of considering the implementation of a bus terminal, one could also consider shared bicycles, bus rapid transit, or electric buses that would have a complementary and positive impact on the subway expansion initiative. In the Butantã region (2), where the subway inauguration was accompanied by new fewer pollutant buses, a positive result in terms of NO concentration reduction could be noted. Both Pinheiros and Santo Amaro regions can be considered air pollution hotspots of São Paulo city. The air pollution hotspots present lanes with intense vehicle flow and constant traffic jams (Gately et al., 2017). In these conditions, fuel consumption is higher, and consequently, there is also a higher emission of pollutants (Gately et al., 2017).

Like most urban centers in developing countries, the city of São Paulo has experienced uncontrolled urban growth that results in long daily commutes, especially for the population of lower-income levels (Rolnik & Klintowitz, 2011; Zandonade & Moretti, 2012). Important policies to change this reality, such as urban planning practices and investment in mixed land use and green spaces, aiming at a more compact city based on active transport, are restricted to a more academic sphere and far from being considered or implemented in the governmental sphere in developing countries.

In São Paulo, improvements related to transport and air pollution are more focused on the change in the transport matrix with investment in electric transport, such as electric trains, subways, and buses. Notably, these measures tend to have overall positive impacts. In addition to the positive evaluation of the subway system in São Paulo carried out by da Silva et al. (2012), the renewal of part of the bus fleet and the incorporation of electric buses in certain regions showed positive impacts on the reduction of NO emissions (Nogueira et al., 2019).

However, local analysis of such policies has been neglected. The inauguration of a subway station, for instance, strongly impacts land use. In Madrid (Spain), Calvo et al. (2013) found much higher population growth in areas where new subway stations opened compared to other areas of the city. According to the authors, this reveals how a subway station changes the local dynamics, so transport planning must be considered jointly with land use planning (Calvo et al., 2013). In a bibliographic review, Samelo et al. (2021) highlighted among the main socioeconomic impacts of the expansion of the subway network: the economic development close to the stations, especially in the service and commerce sectors, and the increase in the value of the properties that result in upper-income levels living in these areas.

The elevated number of people who pass through the three evaluated subway stations indicates that these stations may take thousands of vehicles out of circulation. In this sense, the tendency of increasing air pollution emissions due to the individual vehicular fleet would be worsened if the subway expansion had not occurred. Thus, this study encourages subway network expansion, however, highlights the need for this expansion to be integrated with other environmental policies. Specifically, in São Paulo, we recommend the creation of perimeter lines to make subway transportation a possibility in more regions of the city and to reduce the need of the bus to access the main stations or regions. This type of line would also reduce the overload on the existing lines.

As highlighted by Goel and Gupta (2015) when they studied the impact of the Delhi Metro on air pollution, we reinforce the need for the expansion of the subway network to be accompanied by cost–benefit studies and also by other emission reduction measures, such as better feed systems, cycle paths integrated with the public transportation, improvements in the bus rapid transit system, and parking pricing in the city (Goel & Gupta, 2015). These measures could also be applied to the São Paulo municipality, which would promote an improvement in transit fluidity and air quality. According to Pereira Barboza et al. (2022), in São Paulo, air pollution, insufficient green space, and excess heat are responsible for 11,372 deaths per year and certainly improving current urban and transport planning practices would reduce this negative impact.

These measures would be adherent to several of the Sustainable Development Goals, such as number 3 ("Ensure healthy lives and promote well-being for all at all ages"), 7 ("Ensure access to affordable, reliable, sustainable, and modern energy for all"), 11 ("Make cities and human settlements inclusive, safe, resilient and sustainable") and 13 ("Take urgent action to combat climate change and its impacts"), once subway systems utilize cleaner energy, provide a better level of quality of services, promote sustainable cities, and act preventing climate change and providing a balanced and better health condition (United Nations, 2015).

Thus, the change in the transport matrix toward a less polluting model involves a series of public policies in the areas of transport itself, land occupation, and population awareness (Goldman & Gorham, 2006; Santos et al., 2010). Regarding the passengers transport sector, the literature is unanimous in pointing out active transport and public transport as modes that should be privileged (Santos et al., 2010). Policies aimed at active transport include promoting changes in land use, encouraging mixed land use and compact cities, and also connecting different regions to public transport stations (Cass & Faulconbridge, 2016; Gomez et al., 2015; Kelly & Zhu, 2016; Stevenson et al., 2016). Public transport is considered the solution for longer commutes and should be encouraged over car use, which should be discouraged through policies such as urban tolls and parking limitations (Batty et al., 2015).

Finally, some limitations of the study should be pointed out. The first one is the limitation of the studied regions. The pairing between subway stations and air quality monitoring stations with time series in the required period resulted in only three regions (Pinheiros, Butantã, and Santo Amaro). Coincidentally, the three regions are transport hubs. In the case of Pinheiros, there is a train station and a bus station in addition to the subway station. In Butantã, the subway station also houses a bus station. Finally, in Santo Amaro, the station complies with both a subway and a train station. This characteristic hampers only the inauguration of the subway station to be investigated. The difficulty is very evident in the case of Pinheiros' region where there was the opening of the bus terminal next to the subway station in the analyzed period. Although it proved to be a limitation for the study, this characteristic reveals the importance of integrating transport policies aimed at improving air quality. The second limitation of the study was the impossibility to analyze other pollutants such as carbon monoxide (CO). The time series for this pollutant was not enough to fit the model. As it is a pollutant mostly emitted by cars in São Paulo, if we could have evaluated CO concentration during the period, we could have found more positive results. To access the CO concentration improvement due to the subway expansion represents an interesting theme for future investigations.

Conclusions

The presented results indicate that the subway expansion itself contributes partially to the local air quality improvement, making it necessary to adopt complementary measures in order to guarantee a sustainable trend of advancing the gains in reducing pollutant concentrations in urban centers. In Pinheiros, after the inauguration of the subway station, there are downward trends for the NO, NO_2, and NO_x concentrations. However, these trends were not significantly different from the ones observed before the intervention. In Butantã, only regarding the pollutant NO, it was possible to identify a significant air quality improvement and an alteration in the seasonal behavior after the subway station inauguration. In Santo Amaro, it was not identified any trend in the PM_{10} concentration during the 21 years considered in the analysis.

It is important to emphasize the impossibility of considering pollutants such as CO and CO_2, which are more commonly associated with vehicles' emissions. However, it is also important to note that the minor reduction in the concentration of local pollutants after the inauguration of the subway stations is due to other regional interventions that occurred during the analyzed periods. These interventions, such as the bus terminal implementation near to the subway station, goes in an opposite direction, since we found that it balanced the air quality improvement due to the reduction in car and bus traffic. It also could have attracted traffic flow and habitational density. So, the main result of this study reinforces the need for transport policies and urban planning approaches to be adopted in an integrated manner, also aiming to improve air quality.

Thus, this work encourages the expansion of the subway network associated with other complementary measures that promote the reduction of air pollution, such as traffic restriction, fleet renewal, cycle paths integrated with public transportation, and parking pricing in the city to dissuade the use of private vehicles.

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Declarations

Competing interests The authors declare no competing interests.

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