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Evaluation of atmospheric NO_2 levels in public transport corridors

Avaliação dos níveis de NO_2 atmosféricos em corredores de transporte público

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ABSTRACT
The objective of this work is to evaluate the operational plan for public transport in NO_2 concentration levels. Poor air quality affects the environment, the health of the population and the economy, which requires special attention to the issue. The transport sector is the one that most impacts on air quality in urban centres, with emphasis on heavy vehicles, which represent the majority of the public transport fleet. There are several alternatives used to improve this system, such as exclusive bus lanes, often seeking gains in operational aspects, without considering the environmental impact of the system. Thus, in this study, transport corridors were evaluated in the city of Fortaleza-CE, through the association of passive NO_2 sampling and the selection of road pairs with similar physical and operational characteristics, in order to enable comparative analysis. Sampling was carried out over a year of observations, seeking to verify the influence of traffic conditions, as well as meteorological conditions. The results obtained show that on roads with an exclusive lane for public transport, there is a positive influence on NO_2 concentration.

RESUMO
O objetivo deste trabalho é avaliar níveis de NO_2 em diferentes situações operacionais em corredores de transporte público. A má qualidade do ar afeta o meio ambiente, a saúde da população e a economia, o que requer atenção especial ao tema. O setor de transportes é o que mais impacta na qualidade do ar nos centros urbanos, com destaque para os veículos pesados, que representam a maior parte da frota do transporte público. Diversas são as alternativas empregadas para melhoria desse sistema, como as faixas exclusivas de ônibus, buscando-se, muitas vezes, ganhos em aspectos operacionais, não considerando seu impacto ambiental. Assim, neste estudo, foram avaliados corredores de transporte no município de Fortaleza-CE, por meio da associação da amostragem passiva do NO_2 e da seleção de pares viários com características físicas e operacionais semelhantes, de forma a possibilitar uma análise comparativa. As amostragens foram feitas ao longo de oito meses, buscando verificar a influência das condições de tráfego, bem como as meteorológicas. Os resultados obtidos apontam que nas vias com faixa exclusiva para transporte público, há influência positiva na concentração de NO_2.

1. INTRODUCTION

Air quality is directly related to the health of the population, the environment and even aspects such as infrastructure and conservation of historic monuments, impacting various sectors of the economy. The Pan American Health Organization - PAHO, a body linked to the World Health Organization, presented a report in 2018 pointing out that 91% of the world population is exposed to risks arising from inappropriate air quality, with an estimated 12% of deaths in the world have a relationship with this phenomenon. In Brazil, the report points out that 51,000 people died in 2016 from causes related to air pollution (WHO, 2018). In comparative terms, for the same period, the Institute for Economic and Applied Research (IPEA) pointed out that 65,000 deaths resulted from urban violence; the National Road Safety Observatory (ONSV) estimates that, in 2016, 37 thousand people lost their lives as a result of traffic accidents (IPEA, 2019; BRAZIL, 2018). The consequences of air pollution also affect public coffers. Conte (2010) carried out a study on the expenses of the public health system in the city of Gama, DF, estimating a cost of US$ 1.16 million for the Hospital Regional do Gama in 2004, considering all costs related to care for diseases respiratory and pulmonary disorders, such as hospital maintenance and salaries. Rocha et al. (2020), in their study on predictive scenarios for the reduction of air pollution and associated costs in Fortaleza -CE, reported that a reduction of particulate matter (PM 10) by 5 $\mu g.m^{-3}$ would have avoided more than 130 hospitalizations due to cardiorespiratory diseases per year and a decrease of $62,631.84 in monetary terms.

However, there are differences between the atmospheric pollutant gases that have a local impact (on health, microclimate, buildings, etc.) and the greenhouse gases that contribute to global warming. Pollutants such as particulate matter (PM), heavy metals, ammonia (NH_3), sulfur dioxide (SO_2), nitrogen oxides (NOx), non-metallic volatile organic compounds (VOCs) and carbon monoxide (CO) exert great influence on local effects. Nitrogen oxides, non-metallic volatile organic compounds, carbon monoxide, methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), act for a global effect (MCKINNON et al., 2015). It is noteworthy that urban centres are responsible for approximately one-third of global emissions, originating from anthropogenic sources, comprising: 35% of CO2; 29% NOX; 27% PM10; 26% CO; and 37% SO2 (European Commission, 2018; Esch et al., 2017; Crippa et al., 2021). Among the pollutants listed, Nitrogen Oxides are made up of different substances and are highlighted, especially in urban areas, due to the sharp increase in the fleet of motor vehicles in recent years (ALNAWAISEH et al., 2015). According to D'Agosto (2015), the transport activity is responsible for 59% of the concentration of NOx present in the environment, with the main emitting source coming from the incomplete combustion process in vehicular engines (HAGENBJÖRK et al., 2017). The largest proportion of NOx is emitted in the form of NO (90 – 70%), while the smallest proportion is emitted in the form of NO_2 (10 – 30%) (HAGENBJÖRK *et al*., 2017). However, NO_2 deserves to be highlighted, as its presence in cities is directly due to transport (REQUIA *et al*., 2016), that is, it becomes an important indicator for evaluating the effects of the transport sector on air quality. Furthermore, this pollutant contributes to harmful environmental effects on a local and global scale. Although studies indicate, in general, that there are positive impacts on air quality from alternatives such as exclusive lanes for public transport by bus, there is no discussion that presents assessments of the concentration levels of air pollutants in such devices. It is known that operational conditions, physical characteristics of corridors and meteorological conditions in each region interfere in the dynamics of pollutants (TURNER et al., 2012; SOARES et al., 2017; BEL; HOLST, 2018; MURESAN; FRANÇOIS, 2018), however, what is the magnitude of the pollutant concentration on roads with and without public transport corridors? Given the influence of transport systems on air quality in urban centres, this paper seeks to assess how operational strategies adopted for public transport corridors can affect the concentration of NO_2, given its intrinsic relationship with the transport sector. Thus, the work is not focused on the assessment of local air quality per se, but on the comparison between an air quality indicator (NO_2 concentration) on roads with different operational strategies for public transport. In addition to the central objective, the specific objectives and organization of the work are: to describe the pollutants that tend to come from the operation of public transport and their impacts on society (item 2). Summarize discussion about air quality and ways of monitoring (item 3). Present a low-cost methodology for collecting NO_2 concentrations in Public Transport corridors (item 4). Evaluate NO_2 concentrations according to the corridor and operational characteristics (item 5). Evaluate NO_2 levels according to the type of road (item 5). Finally, item 6 presents the conclusions obtained by this study.

2. ATMOSPHERIC POLLUTION AND URBAN ROAD TRANSPORT

Several factors influence vehicle emissions and, consequently, the levels of air pollutants. In the literature, it is possible to find strong correlations between emissions and the time of day, day of the week, land use, climate, traffic volume, type of fuel, vehicle engine, type of vehicle, among others. In some places, relationships are stronger than in others, as they vary with the characteristics and dynamics of each region (FRANCO et al, 2013). For example, the relationship between land use and air pollutant emissions, studies indicate a significant reduction in emissions when residential density increases (FRANK; STONE; BACHMAN, 2000; HONG; SHEN, 2013; HONG; GOODCHILD, 2014; SIDER et al., 2013). This relationship is due to transport demands. Regions with high commercial density tend to attract a lot of travel during the day, increasing global emissions, while residential areas concentrate on commuting. According to Zhang, Matsushima and Kobayashi (2017), the distinct functional classification pathways also present differences in the pattern of vehicular emissions of pollutants. In their study carried out in Changzhou, China, the authors compared land use, information on the road network and the origin-destination matrix and, with the aid of simulators, observed that the collection and arterial roads represent, together, 88% of the emissions region (ZHANG; MATSUSHIMA; KOBAYASHI, 2017). In addition to the greater capacity of the roads, they represent a link between different sectors of the cities, receiving a large part of the traffic, and often house commercial lots in their surroundings, which attract many trips. Regarding the type of vehicle, road transport (cars, trucks, buses and two or three-wheel vehicles) are responsible for almost 3/4 of CO_2 emissions from the transport sector (IEA, 2020). In Brazil, according to data from the SEEG (Greenhouse Gas Emission Estimation System), the energy sector was responsible for 19% of emissions in 2019, with the transport sector being responsible for 38% of this total (IEMA, 2020). Diesel cycle vehicles are the main source of air pollutant emissions in urban areas, especially buses and trucks. When evaluating nitrogen dioxide (NOx) and particulate matter (PM) emissions, they account for 78.8% and 28.3% of the total, respectively, while representing only 15.7% of CO_2 emissions (IPEA, 2011). Of the residues from the incomplete combustion process of diesel, directly or indirectly, some of the most aggressive to intensify the greenhouse effect and to the detriment of population health are nitrogen oxides (NOx), sulfur oxides (SOx), and tropospheric ozone (O_3) (BOSCH, 2005; FREITAS; BILLIONNET et al., 2012; ZHANG et al., 2013; VALLERO, 2014). Nitrogen oxides (NOx) are products of the interaction between atmospheric nitrogen and oxygen at high temperatures, found in combustion chambers. There are seven possible combinations of these elements, the best known being nitric oxide (NO) and nitrogen dioxide (NO_2), the latter being the most aggressive to the environment (CARVALHO JR; LACAVA, 2003; MARTINS, 2005; YANG; OMAYE, 2009). Diesel engines reach higher temperatures, thus having a higher NOx production compared to Otto cycle engines (MARTINS, 2005). NOx are harmful to health and the environment, as they are highly toxic and participate in reactions with free radicals in the atmosphere (BLONDEAU et al., 2005). NO_2 is a highly toxic gas with a characteristic odor, which can reach the respiratory system and cause a burning sensation when in contact with the eyes and mucous membranes. In more severe cases, inhalation of this gas can cause haemorrhage, respiratory failure, and death. In addition, NO_2 participates in the formation of acid rain and photochemical smog (haze contaminated by smoke) (YANG; OMAYE, 2009). NO is a colourless gas that reacts in the atmosphere with oxygen (O_2), ozone (O_3) and peroxide radicals, contributing to the destruction of the ozone layer, together with NO_2 (YANG; OMAYE, 2009). Given this problem, understanding the relationship between the transport system and air pollution in the impact of air quality is necessary, especially with regard to the public transport system.

2.1. Vehicle emissions and public transport

The public transport system is essential for mobility in urban centres. It provides access for millions of people (captive or not in this segment) to work, school, leisure, etc. In Brazil, it is estimated that 40 million people use buses as an element of public transport per day, which represents 86.3% of this mode's share in public transport (NTU, 2018). Thus, it is natural that many planning policies are geared towards this modality. Among the various solutions used, we can highlight express lines, tariff integration, and exclusive bus lanes or lanes. It is important to highlight that public transport systems in Brazil massively use diesel cycle vehicles.

The exclusive bus lanes or corridors, which can be of the BRT or BRS type (Bus Rapid Service or Rapid Bus Service), are traffic lanes where buses operate, which may or may not be exclusive, and which may have physical barriers to general traffic, such as BRT. In some situations, even in exclusive lanes, turning to the right by other vehicles is allowed. The fact is that exclusive lanes have impacts on the operation of transport systems and bring changes in the way drivers are driven, whether public transport or general traffic. Such situations bring changes, including in emission levels, as they are associated with the way of driving, as well as a reorganization of local traffic.

Yu and Li (2014) analyzed field emissions from a bus line in Nanjing, China, without considering dedicated lanes, and found that about 20% of CO_2, CO (22%), NOx (20%) and HC emissions (21%) are generated close to bus stops, considering deceleration, waiting time and acceleration, representing 19% of the route time. Time at intersections (closed traffic lights) represented 20% of the total, however, with 31% of CO_2 emissions, 34% CO, 30% NOx and 34% HC. The travel time (61%) was responsible for 48% of CO_2, 44% of CO, 50% of NOx and 45% of HC.

The increase in the number of vehicles on the lane favours the occurrence of stop-and-go and also hinders the access of the bus to the stop, making it necessary to stop a few times before entering or leaving it. The study also found a slight increase in emissions on smaller arterials, compared to larger, collectors and local arterials, as on these, traffic tends to be more complex and dense as there are fewer lanes.

Muresan and François (2018) observed that services such as BRT and BRS can improve air quality conditions, but this would not be true for all systems, times of day, pollutants or in charged urban areas. Thus, the implementation of exclusive public transport corridors can improve the problem of air pollution in urban centers.

3. AIR QUALITY AND MONITORING

Emissions, by themselves, do not determine air quality, as it is the product of the interaction of a complex set of factors among which the following stand out: the magnitude of the emissions; the topography; the meteorological conditions in the region, favorable or not to the dispersion of pollutants; and solar radiation. Radiation is also an important NOx oxidation factor, and consequent formation of O_3 (YANG; OMAYE, 2009). Air quality is a matter of extreme relevance and impact on different sectors of society. Monitoring the levels of pollution in the composition of the local atmosphere is essential for understanding the phenomena, for taking actions aimed at improving the indicators, and also for verifying whether the actions taken were effective.

As a way to assess pollution levels, there are techniques for monitoring air quality, with active processes being the most widespread (CAMPOS et al., 2010; HAGENBJÖRK et al., 2017). However, this type of monitoring is usually expensive, requires specialized labour to carry out the collection, constant maintenance of the sampling equipment and also requires electrical energy for its operation. In turn, passive processes capture pollutant samples from the atmosphere in the form of steam or gas, without involving the need for an active airflow, ie, induced by a mechanical process. The passage of air, in this case, is controlled by physical processes, such as diffusion or permeation. Thus, passive methods do not require electricity or specialized labour and allow high spatial resolution of the sampling (CAMPOS et al., 2010), as they are of low cost and easy to operate, it is financially viable to have monitoring continuous in multiple locations at the same time.

The passive method uses small supports attached to an average height of 3 m that house filters soaked in specific absorbent solutions for each type of pollutant. The gas passes through the compartment through permeation and is retained due to chemical reactions with the solution. The filter is then analyzed in order to determine the amount of pollutant retained in it. Using Fick's First Law, which addresses the diffusion of substances in a medium, an average level of pollution can be stipulated.

Deforest et al. (2015) used passive samplers for weekly monitoring of NOx and O_3 levels in five US counties for two months. For NOx, it was observed that there is statistically significant variation between counties, but little variation over the weeks. The place with the highest concentration of this pollutant was not the one with the highest vehicular flow, which can be explained by the wind direction in the region (which is impacted by the zone with the highest flow) and the nearby air traffic. The same could be observed for O_3, however, with greater weekly variation in concentrations. The interesting point of this work includes the participation of the community in the project. With the perception of the levels of air pollutants, residents were able to take actions aimed at improving the region's air quality.

Daris et al. (2015) conducted a study on the contribution of traffic to air quality in the city of Passo Fundo/RS. The authors monitored NO_2 and O_3 levels through passive samplers at critical traffic points; and on roads with commercial and residential standards, as well as a point at the University of Passo Fundo. It was observed that the points with the greatest congestion, despite not necessarily being the ones with the greatest flow, had the highest NO_2 and O_3 values throughout the year; and the point with the lowest flow had the lowest concentrations.

Santos and Souza (2018) measured the level of NO_2 on the university campus of the Fundação Hermínio Ometto with passive samplers. The equipment was placed next to the university entrance and exit control booths. In the study, it was found that during the school period there was an increase of around 40% in the average pollutant compared to the period without classes when the flow of vehicles is reduced, which indicates the influence of internal traffic on air quality.

Dias (2018) and Ribeiro et al. (2019) presented studies aimed at assessing air quality and its relationship with transport systems in the city of Fortaleza – CE, using passive NO_2 sampling. The results obtained by the works showed that the range of variation found for the pollutant was between 0.19 µg/m3.h-1 to 65 µg/m3.h-1, showing that the values obtained were directly related to the volume of traffic, the use of the land and the functional classification of the roads.

4. METHODOLOGY

As mentioned in the previous chapters, one of the main sources of air pollution in urban areas is the transport sector. Within it, the public transport system stands out, consisting mainly of buses, which respond to almost 80% of NOx emissions in the Brazilian urban context (IPEA, 2011). Thus, it was chosen for analysis in this work. In the present study, field collections of NO_2 concentration measurements were carried out in pairs of roads with and without exclusive bus lanes, to allow for comparison between them. Together, the categorized collection of traffic and the collection of meteorological data took place.

4.1. Selection of the study site

As there is no prior and subsequent monitoring of these pollutants on the roads where exclusive lanes were implemented, it was decided to monitor pairs of corridors with similar physical and functional characteristics, whose main difference is the presence or absence of the exclusive lane. In this way, an attempt is made to assess how this operational difference can impact the levels of pollutants. The selection considered the following criteria: Road functional classification; Number of tracks; Number of lanes; Number of usual daytime bus lines; Geographical orientation in the city; Commercial land use; Residential land use. Such information was provided by the municipal authority. Figure 1 shows the areas and routes selected for the study, with description in Table 1.

4.2. Passive pollutant sampling

The technique adopted for the collection of pollutants was passive sampling, as it is a simpler and less expensive alternative, and, as it does not require electricity, it allows the simultaneous monitoring of a large number of points, to enable the expansion of analyzes for regions with different economic situations and attest to one more benefit for the implemented solution, providing more alternatives to urban planning. Thus, the method adapted from Campos et al. (2010) to collect NO_2 concentration data. This method is characterized by the use of samplers that allow the diffusion or permeation of air by natural physical processes and that allow the reaction of the gases of interest with an absorbing solution present in a filter placed inside the sampler. Figure 2 presents the scheme of a set of samplers.

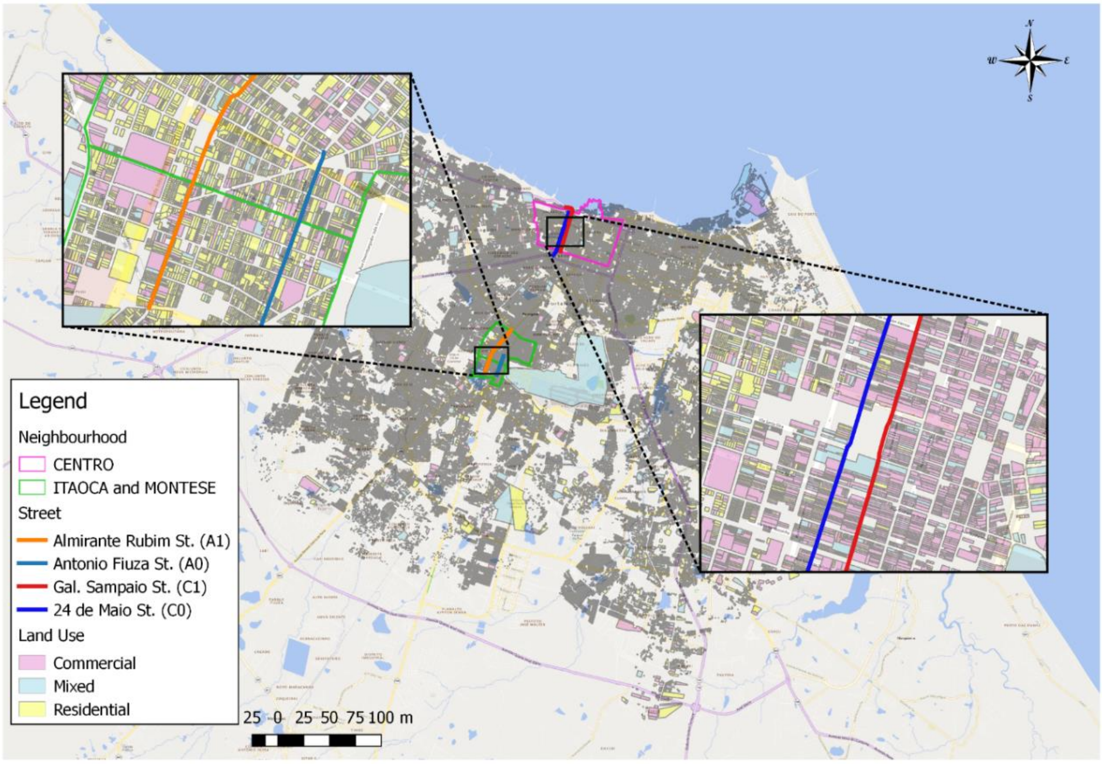

Figure 1. Study areas and selected routes

Table 1 - Routes description

Name	Classification	Bus lane	Bus lines	Lanes	Tracks	% LU Com.	% LU Res.	Code
Alm. Rubim St.	Arterial	Yes	12	2	1	28	65	A1
Antônio Fiuza St.	Arterial	No	10	2	1	31	58	A0
Gal. Sampaio St.	Commercial	Yes	64	2	1	82	16	C1
24 de Maio St.	Commercial	No	60	2	1	71	19	C0

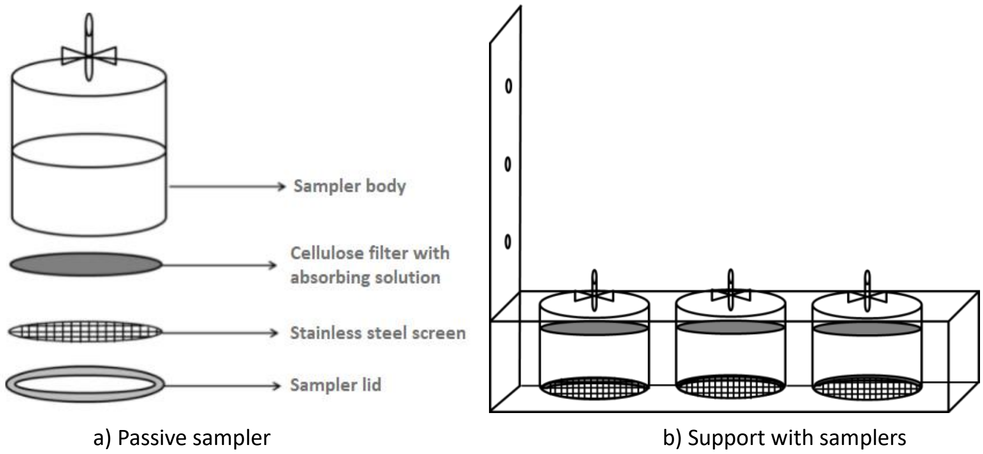

Figure 2. Illustrative schematics of the sampler and support. Source: Ribeiro et al. (2019).

To prepare the passive samplers, it was first necessary to wash them with dertec (Extran, Merk) and deionized water, allowing drying at room temperature. Then, the absorber solution was added to each cellulose filter (Φ = 25 mm), allowed to dry in a vacuum desiccator for 30 minutes, and then inserted into the samplers. They were stored in airtight bags and conditioned at a temperature of 4ºC until the moment of sampling (CAMPOS et al., 2010). After selecting the pairs of lanes, it was determined that the position of the sampling points would be close to the bus stops along the lanes. This positioning is considered the most critical place concerning the emission of pollutants, due to the stop-and-go of vehicles. Thus, each lane was divided into sectors (approximately 300 m each, depending on the distance between stops) and in each sector, two sets of samplers were installed (as shown in Figure 2), one on each side of the lane. Each exchange, carried out every three weeks, was considered as a sampling batch and, at the end of the research, 12 batches or campaigns were obtained, corresponding to the period from march to december.

4.3. Road traffic and weather data

Traffic data were obtained through counts on the studied roads, throughout the pollutant sampling period. The counts were categorized and lasted 8 hours a day, divided into 2 periods: 8:00 to 12:00 and 14:00 to 18:00. Collections always took place on Wednesdays due to the representativeness of vehicular traffic (GAO, 2007). The volume of each vehicle category was counted in the first 15 minutes of each hour, later projected to the hour, over the eight hours; except bus volumes, which were counted for the entire hour. The average results of the counts are shown in Figure 3.

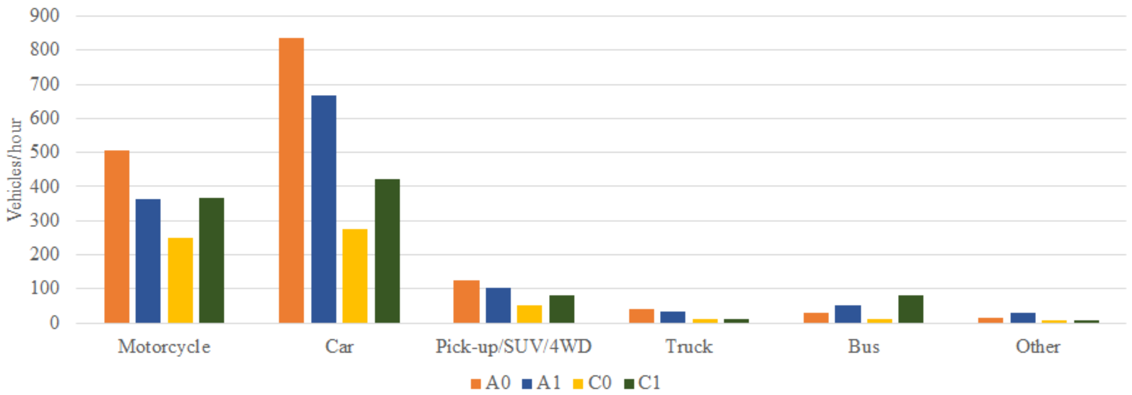

Figure 3. Average categorized vehicle volume

The Meteorology and Water Resources Foundation of Ceará (FUNCEME) and the Meteorology Institute (InMet) made available the meteorological information for the period of analysis, in Table 2. Such information will help in the diagnosis of air quality on the runways. Table 2 also shows the NO_2 concentrations for each campaign carried out.

Table 2 – Average values of humidity in %, wind speed in km/h during the 12 campaigns.

Variables	Rainy season						Dry season							
	1°	2°	3°	4°	5°	Avg.	6°	7°	8°	9°	10°	11°	12°	Avg.
Relative humidity (%)	90.0	86.9	85.8	82.3	76.3	84.3	74.1	71.8	68.2	66.0	66.7	66.6	65.8	68.5
Wind speed (km/h)	4.4	4.6	5.9	6.5	7.4	5.8	8.0	9.2	10.7	11.8	12.2	12.0	11.1	10.7
Temperature (°C)	26.4	26.8	22.9	27.1	26.9	26.0	26.6	26.6	26.7	27.1	27.3	27.4	27.8	27.1
Precipitation (mm)	13.8	10.7	17.9	10.1	9.6	12.4	6.2	2.7	0.9	0.5	0.5	0.4	0.0	1.6
Conc. of NO_2 C0 (μg/m³/h)	23.8	32.7	22.9	26.5	26.5	26.5	25.0	29.5	24.4	23.3	30.0	24.6	21.3	25.4
Conc. of NO_2 C1 (μg/m³/h)	23.5	24.7	34.0	27.9	22.5	26.5	23.4	20.1	23.2	20.2	16.1	16.6	16.1	19.4
Conc. of NO_2 A0 (μg/m³/h)	21.2	20.7	20.8	18.8	19.4	20.2	18.9	16.8	19.5	20.8	15.5	19.7	18.1	18.5
Conc. of NO_2 A1 (μg/m³/h)	25.2	24.7	25.3	30.9	21.5	25.5	26.2	24.0	27.5	23.7	18.9	24.2	20.2	23.5

4.4. Analysis of concentrations and results

The analyzes of NO_2 concentrations were performed in the laboratory using the UV-Vis spectrophotometry technique (CAMPOS et al., 2010). The equipment emits radiation in the ultraviolet and visible range and checks how much is absorbed by the sample molecules, providing absorbance data, which are converted into mass according to the most recent calibration curve (SKOOG et al., 2005). In possession of the obtained mass, Fick's Law (Equation 1) is then applied, which combined with: temperature, pressure, the molar mass of gas and air and molar volume of gas and air, allows obtaining concentration (NELSON, 1992).

$$C = \frac{m.L}{D.A.t} \quad (1)$$

C: pollutant concentration (μg/m^3/h);

m: analyte mass (μg);

L: total length of diffusion path, or sampler height (m);

D: gas diffusion coefficient (m^2/h);

A: diffusion path cross-sectional area (m^2);

t: sampling time (h).

Consequently, a descriptive statistical analysis was performed, verifying the validity and significance of the data. To assess the effects on each pair of lanes (with lane and without lane), whether or not there would be differences between the levels of NO_2 observed in each set, thus indicating whether exclusive lanes tend to result in lower levels of pollution. In addition, non-parametric tests were used for sample comparison (Wilcoxon and Mann-Whitney) in order to obtain indications of the relationships between pollutant levels and road characteristics. Non-parametric tests are recommended for trend analysis in time series, as the original characteristic of these data is non-normal and presents positive asymmetries. To verify the presence of trends, the Wald-Wolfowitz, Cox-Stuart and Mann-Kendall tests were used (SONALI & NAGESH, 2013). A spatial analysis of the observations was also carried out, through the analysis of spatial correlation, to identify the existence of spatial patterns that could help in understanding the results. Initially, the area was divided into polygons using the Voronoy method and later the Moran index was calculated to identify the spatial distribution of these observations.

5. DISCUSSION OF RESULTS

For each route, the average value of all collection points in each campaign was considered, considering the radius of influence of the pollutant dispersion in the samplers, whose results (in μg/m^3/h) are shown in Figure 4. that the values are within the limits found in other studies carried out in the city of Fortaleza (DIAS, 2018; RIBEIRO et al., 2019). Although the values found are lower than those established by CONAMA Resolution 491/2018, the comparison of the results presented here cannot be rigorously compared to the normative, as the sampling method used here differs from that established by the resolution. However, as the objective is not the quantification of local air quality, but the comparative analysis of transport systems, it is understood that the methodology used here is adequate to achieve the established objectives.

In the collection referring to the third batch, a section of the A0 road was blocked for works, reducing the flow at this location, which may justify the reduction in concentration in this interval. In lot 4, C1 shows a concentration peak that may be related to a protest, which forced a diversion of traffic through the region, resulting in major congestion in the surroundings.

In turn, in the tenth batch, there was, in the State of Ceará, a public safety crisis that resulted in a reduction of up to 70% in the fleet of buses in circulation. The impact on air quality was verified, with a reduction in the concentration of NO_2 in all roads, except for the A0 road, which, being a connection road between two regions of the city, there was an increase in the number of private vehicles. Starting with lot 10, in the same period, renovation works were started on the lanes surrounding the VLT (Light Rail Vehicle) station, close to the A0 and A1 lines. These activities affected the A1 road, which had part of its flow diverted to adjacent streets, which may have contributed to the variation in the concentration on this road. Utilizing trend tests, Wald-Wolfowitz, Cox-Stuart and Mann-Kendall, a trend towards a decrease in NO_2 concentrations was verified in all lanes along the analyzed period, except for A0. This situation may be associated with the fact that it is an arterial route that has not suffered severe variations in flow. Routes C1 and C0, located in the city centre, justify their downward trend due to the works carried out by the city hall that diverted traffic in the surrounding area. This phenomenon can be observed in the temporal decomposition shown in Figure 5.

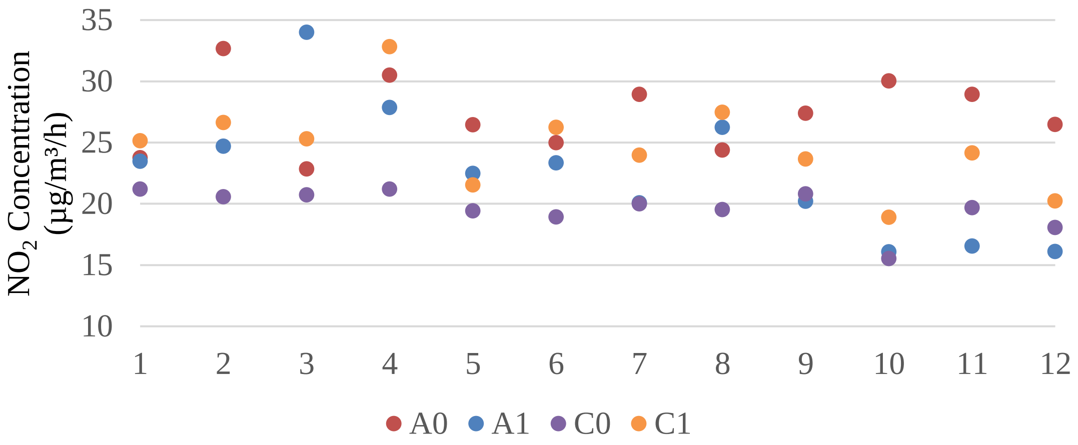

Figure 4. NO_2 concentrations in arterial and commercial routes. Source: Prepared by the Authors (2020).

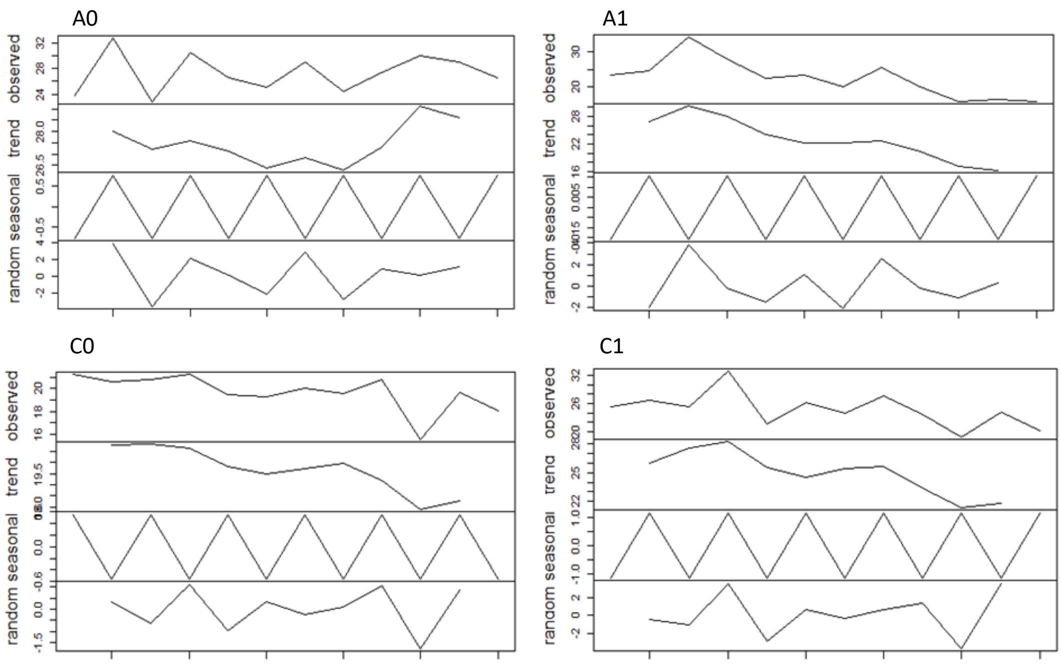

Figure 5. Temporal decomposition: NO_2

From the boxplot in Figure 6, built with all observations of each lane over the 12 collections, it is possible to see a greater presence of outliers in C1. It is noteworthy that road C1, when compared to C0, has more vehicular traffic in all categories (Figure 3), in addition, the area in which road C1 is located has an intense presence of the informal market. The combination of all these facts favours the low operational performance of the road, from a vehicular point of view. The low operational performance of the C0 pathway makes the median of the NO_2 concentrations similar to that of A0, as shown in Figure 6. Analyzing the histograms in Figure 7, a similarity of distributions regarding the pathways can be observed. With that, we can assume a similarity in the issuing profile of each way. This fact may result from the composition of the fleet passing through the analyzed routes. The hypotheses raised arising from the analysis of Figures 6 and 7 will be tested later using non-parametric tests.

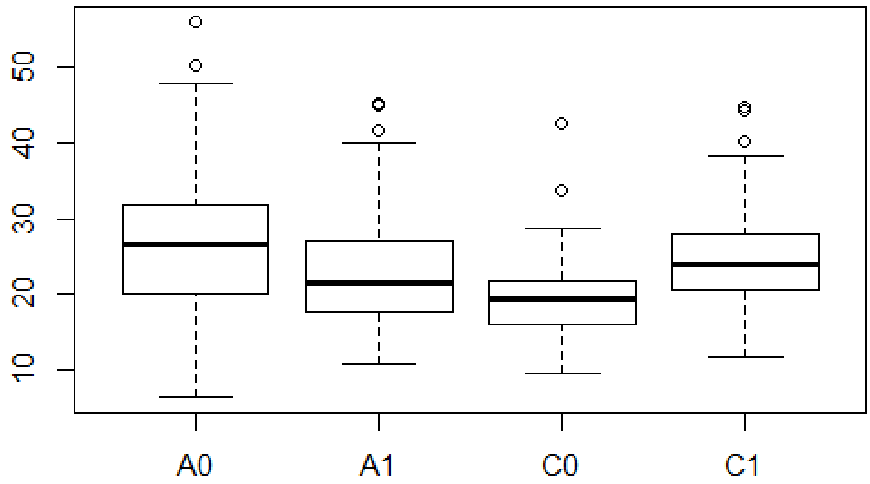

Figure 6. Boxplot: NO_2 level

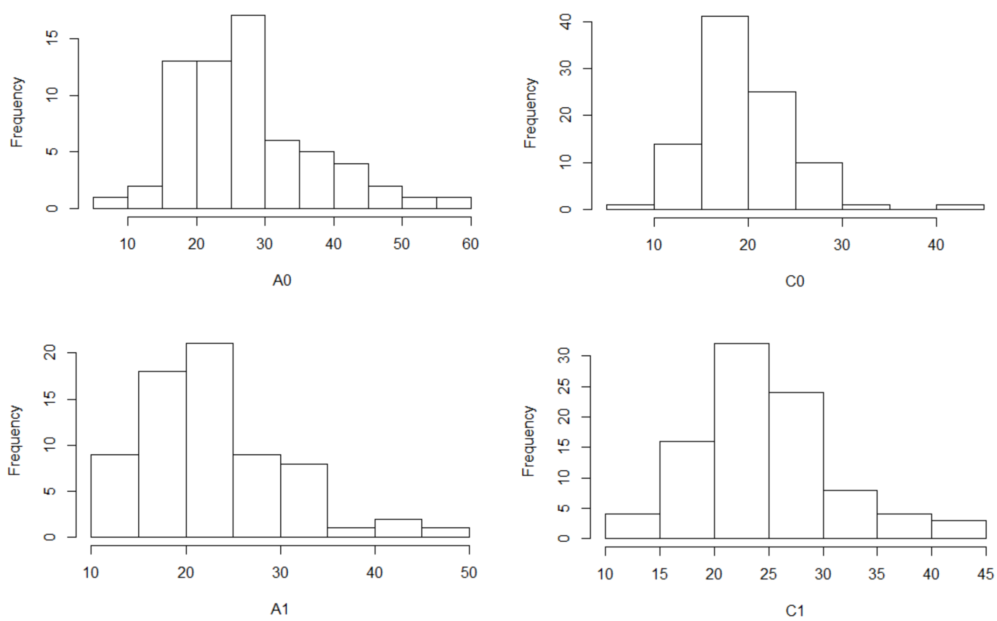

Figure 7. Histogram of lane distribution: NO_2

After treating the outliers, the mean NO_2 concentration was calculated for each road, in each campaign, and allowed for correlation analysis between the NO_2 levels and the meteorological factors considered, making it possible to establish a relationship between the variables (Table 3). All routes, except the A0, presented values above 0.23. Possibly, for route A0, other factors may exert a stronger influence on the atmospheric concentration of the pollutant, such as vehicular flow, since it was the route with the highest flow among the four under study, and which showed a tendency to increase the concentration, on the contrary of others.

Table 3 – Analysis of NO_2 correlation versus Meteorological Factors

	Wind speed	Precipitation	Temperature	Insolation
A0	0.07	-0.20	-0.45	0.12
A1	-0.69	0.72	0.81	-0.76
C0	-0.42	0.51	0.38	-0.65
C1	-0.40	0.27	0.24	-0.53
overall average	-0.59	0.54	0.48	-0.73

We can observe a highlight for the negative relationship of wind speed and insolation with the pollutant. The results are consistent with the literature, where the wind helps in the pollutant dispersion process, reducing its concentration in the environment; and sunlight (or radiation) participates in the reaction process of NO2 with other gases, such as O3. The positive relationship obtained for precipitation does not agree with the literature, where NO2 reacts with water to form HNO3 (aq) (acid rain), reducing its concentration in the environment (YANG; OMAYE, 2009). However, the rainy season, despite helping to "clean" the atmosphere, also causes a decrease in the average speed and, consequently, increases congestion, which may explain this result. Due to the number of observations, non-parametric tests were performed to compare routes, to evaluate whether the hypotheses raised through the analyzes are statistically significant. We chose to evaluate the routes within the same functional classification; with distinct classification; the presence of the exclusive public transport lane. To this end, the Wilcoxon and Mann-Whitney tests compare samples to find out if they belong to the same population, whose results are shown in Table 4.

Table 4 – Comparison tests of sample means of NO_2 concentration (α = 1%)

	Teste de Wilcoxon	Teste de Mann-Whitney
A0 x A1	Reject	Reject
C0 x C1	Reject	Reject
A x C	Does not reject	Does not reject
0 x 1	Does not reject	Does not reject
A x C0	Reject	Reject
A x C1	Does not reject	Does not reject
(A0+A1+C1) x C0	Reject	Reject

When comparing pathways with the same classification (A0 x A1; C0 x C1), there is evidence to reject the null hypothesis, that is, belonging to the same population. The results obtained by the tests are an indication that the functional classification and land use are not as influential as the flow of heavy vehicles (buses and trucks) in NO_2 concentrations, as a result of the comparative test between all roads and C0. The result points to the influence of the presence of an exclusive lane for public transport on the NO_2 concentration values, A1 presented results lower than A0, despite a greater volume of heavy vehicles (83 vehicles/h versus 69 vehicles/h).

This reinforces the idea that the exclusive lane favours the fluidity of buses, a fact that reduces stop-and-go events and competition for space, which increases the operational performance of public transport and reduces the category's environmental impacts. In the comparison between (A x C; 0 x 1), there is evidence not to reject the hypothesis of belonging to the same population. When analyzing together the different areas analyzed, as shown in Figure 1, a bias occurs that produces an unexpected result. This fact can be explained by the works that took place in the Centro neighbourhood and affected the vehicles circulation pattern. This fact also explains the results (A x C0; A x C1; (A0+A1+C1) x C0), as the C0 road was the most affected by traffic changes. Finally, the Moran index (t) was obtained for the two areas that house the roads, to verify the existence of spatial correlation in the samples. First, each region was divided into polygons, according to the Voronoy Diagram (Figure 8), to determine the "area of influence" of each point. Afterwards, a sample from the rainy season (L03) and one from the dry season (L12) were selected, as well as the general average value of each point. Finally, the univariate local Moran index was obtained for NO_2 levels and bivariate for "NO_2 versus heavy vehicle flow" (buses and trucks) and "NO_2 versus land use" around the point.

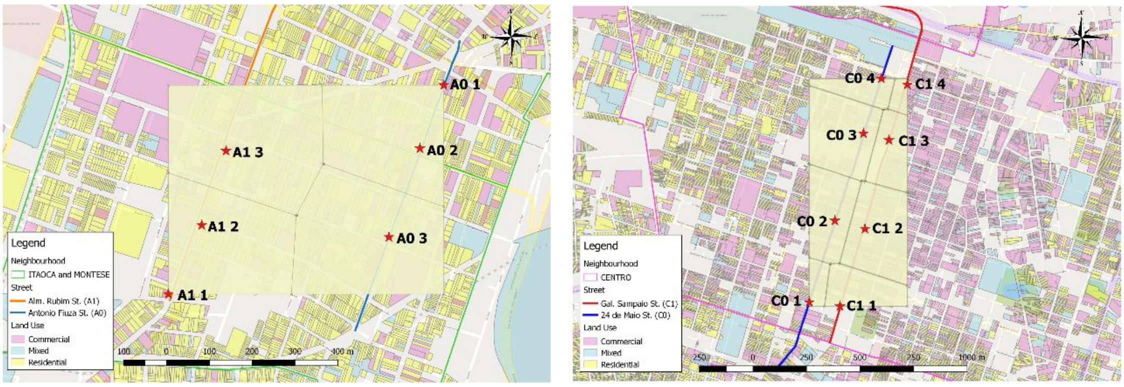

Figure 8. Voronoy Polygons

Table 5 shows the values obtained for the region of arterial and commercial routes. For the rainy season, there is a tendency for spatial correlation, however, when using the bivariate index, this relationship becomes weaker. The opposite occurs for the dry period and the general average, with emphasis on the analysis of NO_2 versus heavy vehicle flow. Thus, there is evidence for a stronger relationship between this pollutant and the variation in the flow of vehicles in the region.

Table 5 – Moran Index: arterial and commercial routes.

Type of way	Period	NO_2	NO_2 x Vehicle flow	NO_2 x Use of the soil
Arterial	Rainy	-0.32	-0.24	-0.22
	Dry	0.16	-0.30	-0.19
	Average	0.07	-0.40	-0.15
Commercial	Rainy	0.14	-0.06	0.14
	Dry	0.42	0.01	0.41
	Average	0.27	-0.04	0.34

For commercial routes, the test showed different results. While the values remained low for the rainy season, demonstrating a low correlation in the three analyses, the results for the dry season and the general average showed correlation indications in the univariate analysis of NO_2

and the bivariate NO_2 versus land use analysis. Thus, it is observed that, in this region, land use exerts a stronger influence on traffic and, consequently, on the levels of this pollutant. From the analysis of the results, it was found that different regions have different patterns of behaviour of the NO_2 level. Meteorological factors, vehicle flow and land use patterns were significant, as well as the exclusive lane effect.

6. CONCLUSIONS

This work proposed to evaluate the NO_2 concentration, given its intrinsic relationship with the transport sector, in public transport corridors, with different operational structures. It was possible to observe indications of influence in the presence of exclusive bus lanes on NO_2 levels. In general, the roads that contained exclusive lines had lower mean levels of this pollutant, and hypothesis tests pointed to this understanding. The result is more evident when evaluating the average flow of heavy vehicles. Exclusive lane roads had lower pollutant levels, even with a higher flow of vehicles in this category. The values found for NO_2 concentration were consistent with those presented by other local studies. However, it is important to emphasize that the focus of this study was not to analyze the local air quality but to verify how the strategies applied to the transport system would affect the levels of pollutants. During the analyses, the volume and composition of traffic were associated with the level of pollutants, as opposed to the functional classification. Roads with a greater volume of heavy vehicles, in general, had higher levels of pollution. When comparing streets with a similar flow, the exclusive lane street exhibited a lower result compared to its non-lane pair. Meteorological conditions were also relevant, wind speed and insolation (radiation) showed significant negative correlation values, while temperature and precipitation showed a positive correlation. Already analysis in terms of regions, land use and flow of heavy vehicles proved to be significant. The first showed a higher correlation with NO_2 levels in the region of commercial roads, where commercial land use is predominant and the roads are narrow. The second, however, was more expressive in the region of arterial roads, where the flow is greater and the use of residential land predominates. Thus, the spatial formation of the surroundings of the roads influenced the pattern of NO_2 concentration. It was possible to find evidence that attests to the improvement in NO_2 levels after the implementation of an exclusive bus lane, where even with the increase in the flow of heavy vehicles, atmospheric concentrations did not worsen. Finally, the results obtained indicate that the prioritization of public transport by bus, portrayed by the implementation of exclusive lanes, brought environmental benefits by observing lower levels of NO_2 on roads with that type of device. In addition to the operational gains, widely discussed in the specialized literature, the benefits brought by the improvement of air quality have a positive impact on the community, as even non-users of the public transport system will be positively impacted, as a result of less exposure to pollution. As relevant points stand out the reduction in the aggravation of diseases potentiated by pollution, potential savings with the health system, reduction of physical complications resulting from cardiovascular and respiratory diseases, in addition to efforts to continuously improve the quality of life of urban populations. Thus, evaluating the environmental aspects resulting from actions in transport systems is important for planning sustainable urban accessibility.

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