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RESEARCH

Urban air pollution evaluation in downtown streets of a medium-sized Latin American city using AERMOD dispersion model

Yamila Soledad Grassi · Mónica Fátima Díaz

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Abstract The transport sector is considered the largest contributor of air pollutants in urban areas, mainly on-road vehicles, affecting the environment and human health. Bahía Blanca is a medium-sized Latin American city, with high levels of traffic in the downtown area during peak hours. In this regard, it is necessary to analyze air pollution using an air quality model considering that there are no air pollutant measurements in the central area. Furthermore, this type of study has not been carried out in the region and since the city is expected to grow, it is necessary to evaluate the current situation in order to make effective future decisions. In this sense, the AERMOD model (US-EPA version) and the RLINE source type were used in this work. This study analyzes the variations of pollutant concentrations coming from mobile sources in Bahía Blanca's downtown area, particularly carbon monoxide (CO) and nitrogen oxides (NOx) during the period Jul-2020 to Jun-2022. It is interesting to note the results show the maximum concentration values detected are not directly associated with maximum levels of vehicle flow or emission rates, which highlights the importance of meteorological parameters in the modeling. In addition, alternative scenarios are proposed and analyzed from a sustainable approach. Regarding the scenario analysis, it can be concluded that diesel vehicles have a large influence on NOx emissions. Moreover, restrictions as strict as those proposed for a Low Emission Zone would be less applicable in the city than alternative temporary measures that modify traffic at peak hours.

Keywords Air pollution · Urban mobility · Bahía Blanca city · Future scenarios · AERMOD model

Y. S. Grassi · M. F. Díaz (✉)
Planta Piloto de Ingeniería Química - PLAPIQUI (UNS-CONICET), Camino La Carrindanga 7000, (8000) Bahía Blanca, Argentina
e-mail: mdiaz@plapiqui.edu.ar

M. F. Díaz
Departamento de Ingeniería Química, Universidad Nacional de Sur (UNS), Avenida Alem 1253, (8000) Bahía Blanca, Argentina

Introduction

The source of air pollution in cities has changed over time, but it is always contingent on energy production (Thornbush, 2015). In all cases of pollution, the following aspects can be distinguished: an emission source; the pollutants themselves; a transport medium—air, water, soil—and a receptor—ecosystems, structures, or individual organisms (Alloway & Ayres, 1993). Undoubtedly nowadays, urban air pollution represents a major concern around the world, both in developed and in developing countries (Gulia et al., 2015a). The growth of urban population and the increase in the volume of motorized traffic has led to a rise in urban air pollution levels (Bari et al., 2023;

Gautam & Bolia, 2019; Gulia et al., 2015a; Singh et al., 2018). In urban areas, the transportation sector is the largest generator of air pollutants, mainly on-road vehicles (Porta et al., 2018), reaching a contribution of 80% in cities (Baldasano, 2020; Gulia et al., 2015a). It is known that mobile sources are considered diffuse or non-point ones, because they cannot be attributed to a specific geographic location (Alloway & Ayres, 1993). This situation makes monitoring and control much more difficult. In addition, the transportation sector is known to be the main anthropogenic source of carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs) as well as sulfur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$), hydrocarbons, among others (Gallego Picó et al., 2012; Porta et al., 2018). In this sense, urban traffic affects the environment and human health (Chandrashekar et al., 2023; Ma et al., 2016; Singh & Gokhale, 2023; Tang et al., 2020).

The main tools used to study and evaluate air quality are monitoring programs, air quality models, and emission inventories (Gallego Picó et al., 2012). The goal of air quality models is to find a relationship between substances that are emitted into the atmosphere, either by natural or by anthropogenic sources, and the concentrations of these substances or others that originate from them in the atmosphere, at given receptors (Porta et al., 2018). The prediction and forecasting of air pollutant concentrations are important tasks of air quality models as this generates crucial information for urban air quality management (Gulia et al., 2015b). In this sense, these models are widely used to evaluate control strategies to reduce air pollution and help in sustainable policy design, as well as to comply with air quality standards (Eslamidoost, et al., 2023a; Singh & Gokhale, 2023; Lestari et al., 2022; Zeydan & Öztürk, 2021; US-EPA, 2019; de la Guardia & Armenta, 2016; Gulia et al., 2015b; Gibson et al., 2013; Misra et al., 2013). It should be noted that air quality modeling allows the analysis of the dispersion of different air pollutants from various sources, such as stacks and flares of industrial facilities (Eslamidoost et al., 2022, 2023a, 2023b), urban solid waste landfill (Kaydi et al., 2022; Khademi et al., 2022), as well as mobile sources, such as vehicles on city streets (Odediran et al., 2024; Singh & Gokhale, 2023; Grassi et al., 2022; Amoatey et al., 2020; Macêdo & Ramos, 2020; Misra et al., 2013). It is known that air quality models have the ability to describe the atmospheric dispersion of inert or reactive species and particulate matter at different scales—local, regional, or continental (Porta et al., 2018). Based on this, it is necessary to have relevant information about the study area, such as meteorology, besides the model's own equations. As long as reliable information is available, air quality models are essential when there is no continuous monitoring network or programs designed to measure pollutant gasses. Undoubtedly, it is of utmost importance to have modeling and monitoring tools, which allow knowing the local reality (Querol, 2018). In this way, actions can be implemented to improve the air we breathe and mitigate urban air pollution, generating evidence-based and sustainable policies.

Bahía Blanca is a mid-sized Argentinian city, which has suffered an unplanned urban growth, generating higher levels of traffic in the city's downtown area due to the increased private car use, a situation known as induced traffic theory associated with urban sprawl (Ferrelli et al., 2016; Gayda & Lautso, 2007; Ortúzar, 2019). Regarding the city's economy, it is home to one of the most important Argentine ports, as well as a large industrial petrochemical complex. Because of this, and the fact that the city has multiple road and rail networks, it is also considered an intermediary city since it functions as a link between different regions of the country and to the rest of the world through the port. The city has 335,190 inhabitants according to the last census conducted in 2022 (INDEC, 2022) and by 2018 the Bahía Blanca vehicular fleet was around 172,000 units reported by Grassi et al. (2021). In view of all the city's characteristics and the fact that there is no monitoring of air pollutants at any point in the city's downtown area, it is interesting to analyze air pollution using air pollutant dispersion modeling. In addition, taking into account the city's characteristics and the fact that there are no in-depth and complete research on the vehicle fleet and its emissions for Bahía Blanca, we consider that is necessary to perform a study of the current air pollution situation generated by mobile sources, especially in view of the medium-term projection for the city. In this regard, it is interesting to note that the start-up of the President Néstor Kirchner gas pipeline (GPNK), which will transport natural gas from the Vaca Muerta oil field, may have an impact on the city. In this sense, the volume of gas reaching the city could be increased, allowing a growth of the city's industrial zone and its potential export through the construction of a liquefied natural gas facility (CREEBBA, 2023). This potential scenario would have an impact not only on the economy of the city and the region, but also on the urban mobility of Bahía Blanca, so it is even more interesting to know the current challenges in order to mitigate them before a possible new urban growth.

The major aim of the present work is to analyze the variations in the dispersion of pollutants coming from mobile sources in Bahía Blanca's downtown area, particularly carbon monoxide (CO) and nitrogen oxides (NOx) during the period July 2020–June 2022 (two full years). It should be noted that emission inventory data from Grassi et al. (2021) indicate that these pollutants are the most emitted by traffic in Bahía Blanca, representing 70% for CO and 22% for NOx of total emissions. By using this methodology, it will be possible to detect the worst-case scenarios that can be generated at present, considering vehicle flow, its emissions, and the prevailing meteorology. Based on this, the worst condition that could have occurred in the studied period can be modeled using the American Meteorological Society/Environmental Protection Agency (AMS/EPA) Regulatory Model (American Environmental Regulatory Model (AERMOD)). Finally, it will be possible to compare these results with the current Argentine legislation and international standards (Air Quality Index), and also propose new modeling scenarios that include more sustainable mobility proposals for the future. This work is of great relevance for the area under study because, as mentioned, there is no air quality or traffic monitoring in the area, and it is known that the city has growth potential and that its vehicle fleet has already increased in recent decades (Grassi et al., 2021). In this sense, the present study collaborates in the generation of reliable and continuous air quality data to help in evidence-based decision-making.

Methods and data

Study area and traffic flow data

The city of Bahía Blanca is a medium-sized urban conglomerate with 335,190 inhabitants according to the last census in 2022 (INDEC, 2022). The city is located in the southwest of Buenos Aires Province, Argentina (see Fig. 1), in the so-called *Llanura Pampeana*. The landscape is characterized by low topographic slopes; the relief ranges from flat to slightly undulating (Perillo & Piccolo, 2004; Kruse & Zimmermann, 2002). The study area is within temperate climates with semi-arid characteristics (Ferrelli et al., 2016). As mentioned in the introduction, Bahía Blanca is considered a strategic logistic node since it interconnects several production areas of the country, considering its road, rail, and port infrastructure.

The points analyzed in this work are located in the Bahía Blanca city downtown, where the vehicular flow at peak hours is known to be high. For this study, the period analyzed runs from July 2020 to June 2022 (two complete years), and the selected monitoring points are shown in Fig. 2, identified by A (Estomba and Roca), B (Sarmiento and Zelarrayán), and C (Brown and Fitz Roy). Vehicle flow data were obtained as presented in Grassi and Díaz, (2023), making a manual count by viewing video fragments from the security cameras of the Centro Único de Monitoreo (CeUM), belonging to the Municipality of Bahía Blanca (MBB). A detailed analysis of the data collection and vehicle flow data used in this work can be found in Grassi and Díaz, (2023). The study was carried on weekdays in the aforementioned downtown intersections, at 8, 12, and 17 h, considered peak hours. It should be noted that the analyzed period was influenced by several restrictions due to COVID-19, and that is why fluctuations in the flow have been detected.

In addition, a segmentation of the local motorized vehicle fleet was performed in five categories: motorcycles (MC), cars, pick-ups, light commercial vehicles (LCV), and buses. Heavy-duty vehicles were not considered within the segmentation because they are forbidden from accessing the study area (microcenter) during daytime hours according to municipal regulation. Each category was further separated by the type of fuel used in their engines—gasoline, diesel, and compressed natural gas (CNG)—considering the national statistics as had been done in Grassi et al. (2021). This segmentation is important for the modeling because the amount of emission depends on vehicle characteristics (Freire et al., 2020). Moreover, each vehicle category was segmented according to emission control technology into Pre-EURO, EURO 1 to 4, and EURO 5. This was carried out using the percentages of occurrence of each segment by direct

Fig. 1 Location of Bahía Blanca city in the southwest of Buenos Aires Province in Argentina

observation of the license plate format of each vehicle. To obtain this information, home videos were made in other downtown areas of the city, as presented in Grassi et al. (2020). At this point, it should be noted that the Argentine vehicle license plate has undergone variations over the years (see Fig. 3). As from January 1, 1995, a new license plate system was introduced in Argentina, which established that vehicle domains would consist of three letters and three numbers. New vehicles as from January 1, 1995, were granted domains from patent AAA-000 to QZZ-999. Vehicles under 1995 were requested to be re-registered, and were assigned domains from RAA-000 onwards. Based on this, and considering the years of implementation of EURO standards in Argentina (Grassi et al., 2021; Vasallo, 2018), it is possible to estimate that vehicles with this last license plate format (RAA-000 onwards) do not follow any EURO standard (Pre-EURO) while those vehicles with AAA-000 format license plate have some emission control technology between EURO 1 to EURO 4 standards. Finally, in 2016, a new license plate format exclusively for brand new vehicles started to be implemented in Argentina. This new license plate has different characteristics from the previously implemented one since it changes its shape and color and

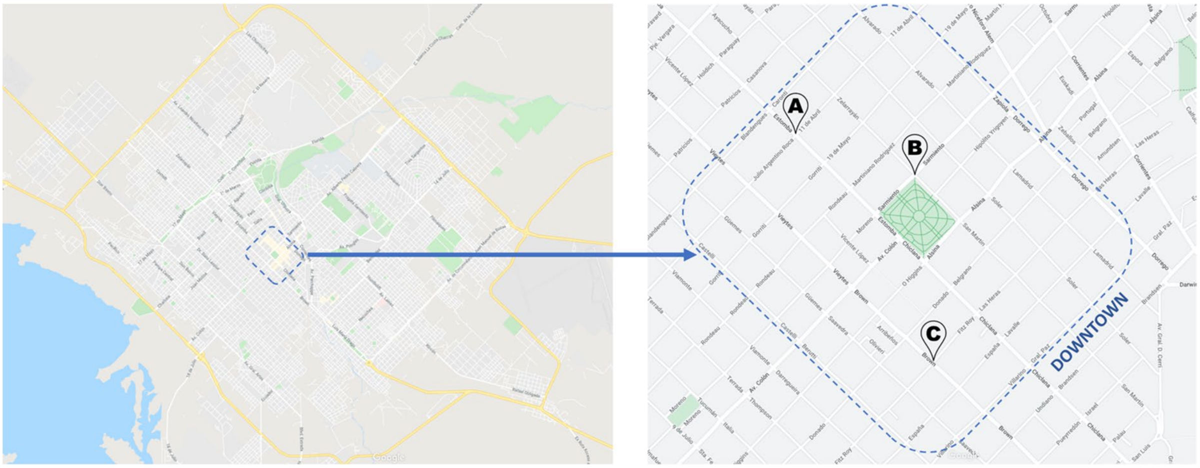

Fig. 2 Location of Bahía Blanca's downtown (left) and the three monitored intersections within the downtown (right), identified with the letter A (Estomba and Roca), B (Sarmiento and Zelarrayán) and C (Brown and Fitz Roy)

contains one more letter, being of the AA-000-AA format (see Fig. 3). Those vehicles that have the 2016 license plate are the ones that follow the EURO 5 standard, since from that year the Argentine legislation requires its implementation (Vasallo, 2018). This sub-categorization is important since it allows the use of more specific emission factors for each vehicle category. In the case of motorcycles, all of them are considered to apply the EURO I standard, as was done in Grassi et al. (2021). In this way, we not only have a categorization by vehicle type but also by emission control technology used.

AERMOD modeling and data analysis

The methodology is based on detailed work similar to that used in Grassi et al. (2022), since other study points are considered in that work. First, we obtained the necessary vehicle flow data for the elaboration of the emission rates (ERs) and then used the latter in the air quality modeling. The AERMOD model (version 19,191), widely recommended by the United States Environmental Protection Agency (US-EPA), was used to perform this work. In particular, the free version downloaded from the US-EPA website was employed (US-EPA, 2019). As in Grassi et al. (2022), the RLINE source type was used, which was designed to simulate roads as line segments with emphasis on estimates of concentrations very close to the source line (Snyder et al., 2013; Valencia et al., 2018). It should be considered that this source type only allows the use of flat terrain. The ER required by the RLINE source type is the source emission rate in [g/(s·m^2)] (US-EPA, 2021a), calculated using the same methodology applied in Grassi et al. (2022), in which the emission factors coming from the COPERT model (EMISIA, 2019), the vehicular flow obtained as explained above (see the "Study area and traffic

Fig. 3 Evolution of the license plate of motor vehicles in Argentina from 1964 to the present

flow data" section), and the particular characteristics of each evaluated street, width and length, detailed in Table 1, are considered.

For this work, the selected receptor grid is a polar one consisting of nine circles of diameter 10, 25, 50, 75, 100, 125, 150, 175, and 200 m, with the center at the midpoint of each intersection analyzed, so there are three polar grids. Each circle contains 36 receptors. It should be considered that the emissions generated by line sources become imperceptible at a distance of approximately 100 m (Amoatey et al., 2020; Misra et al., 2013).

The meteorological files needed to enter AERMOD were developed using AERMET, which was also downloaded from the US-EPA website (US-EPA, 2019). This meteorological preprocessor requires hourly surface observations and upper air sounding (US-EPA, 2021b). The Integrated Surface Hourly Database (ISHD) for Bahía Blanca is obtained from the US–National Oceanic and Atmospheric Administration (NOAA 2022a), while the Santa Rosa city upper air sounding data is employed because data for Bahía Blanca are unavailable, and is the closest to our study area with similar meteorological conditions (see Table 2). This information is also obtained from NOAA (2022b).

According to the wind plot for the period from January 1, 2020, to December 31, 2022, shown in Fig. 4, the predominant wind directions in the city of Bahía Blanca are north and northwest. The average wind speed is 5.21 m/s (18.76 km/h) and the average percentage of calm situations is detected at approximately 1.29%.

The employed meteorological parameters belonged to the day and hour when the traffic flow was obtained. To run AERMET, the albedo, Bowen ratio, and surface roughness were set for Bahía Blanca with the following values: 0.16, 2.00, and 1.00 for summer (December to February); 0.18, 2.00, and 1.00 for autumn (March to May); 0.18, 1.50, and 1.00 for winter (June to August); and 0.14, 1.00, and 1.00 for spring (October to December). These values were extracted from the recommendations given in the User's Guide for the AERMOD Meteorological Preprocessor (AERMET) (US-EPA, 2021b).

Table 2 Annual average of typical climatological data for Bahía Blanca and Santa Rosa (period 1991–2020). Source: National Meteorological Service—https://ssl.smn.gob.ar/dpd/observaciones/estadisticas.txt

	Bahía Blanca	Santa Rosa
Temperature [°C]	16	15
Relative humidity [%]	64	65
Frequency of days with precipitation higher than 1.0 mm	5	5
Cloud cover [eighth]	4	4
Precipitation [mm]	63	53
Wind speed [km/h] (2011–2020)	18	15

The output files are obtained for carbon monoxide (CO) and nitrogen oxides (NOx), as a 1-h average, considering peak hour traffic, to understand the evolution of air pollution dispersion during the days and hours evaluated and to determine worst-case scenario. The results are also compared to the local regulations, which are stated in Decree 1074/2018 from the Environment Ministry of the Buenos Aires Province, Argentina (MA-PBA, 2018). The regulatory framework has been revised in stages since 2018. From October 2022, the following standard values are applied for 1 h average: 40,000 μg/m^3 CO and 188 μg/m^3 NO_2. For the comparison of the results obtained by NOx modeling and the NO_2 parameters established by the current regulations, a tier 1 approach was considered, in which a complete conversion of all nitrogen oxides (NOx) into nitrogen dioxide (NO_2) is assumed (US-EPA, 2020). Also, the results are compared with the Air Quality Index (AQI) international standard (US-EPA, 2018) proposed by the US-EPA, and with the global air quality guidelines established by the World Health Organization (WHO, 2021).

Once this analysis has been carried out, we model possible future scenarios considering changes in the vehicle fleet configuration, not only in quantity but

Table 1 Width and length of each evaluated street section considered for the modeling

	A		*B*		*C*	
	Estomba	Roca	Sarmiento	Zelarrayán	Brown	Fitz Roy
Width [m]	6	6	9	9	9	6
Length [m]	150	150	150	150	150	150

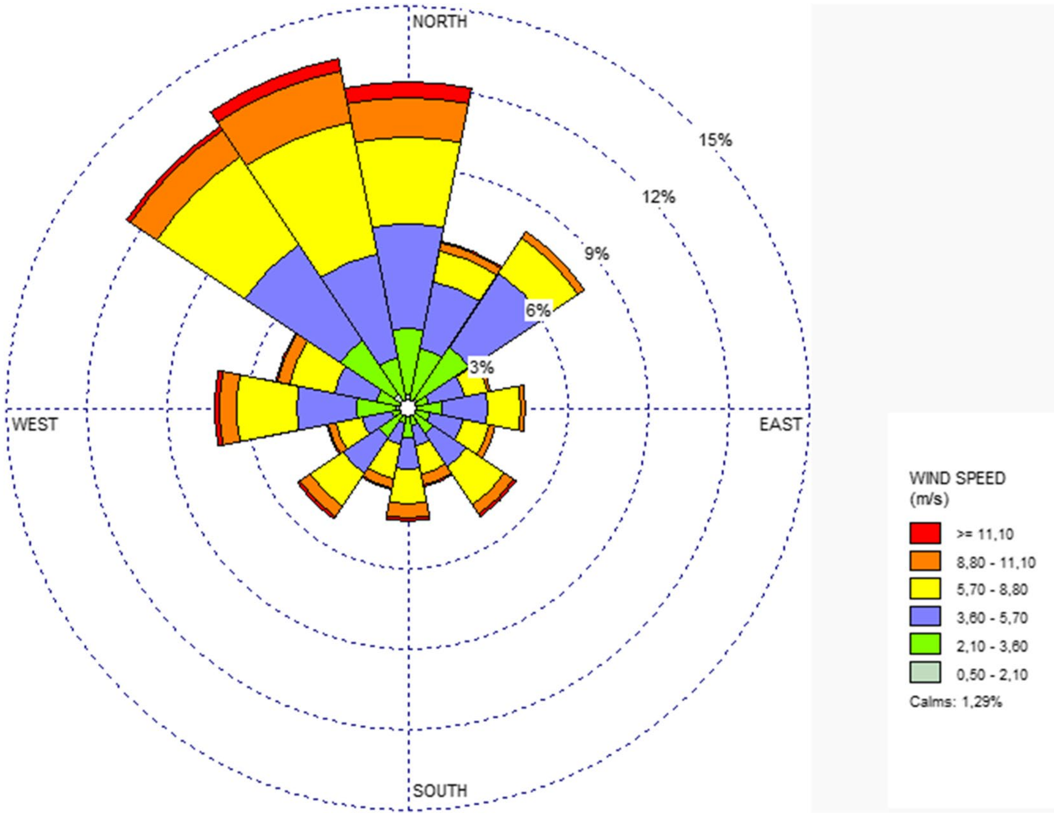

Fig. 4 Wind plot for Bahía Blanca, Argentina (data period: from January 1, 2020, to December 31, 2022)

also in its segmentation. Initially, the worst-case scenario is considered in terms of air quality levels, and then two alternatives to reduce them are proposed. In this way, situations involving the use of more sustainable urban mobility will be contemplated.

Results and discussions

This section presents the results obtained from the modeling with AERMOD using all real parameters, vehicular flow, and meteorology, during the whole period analyzed. In this way, the worst-case scenario conditions are detected and analyzed in order to evaluate and model possible future scenarios.

Air quality analysis considering vehicular flow and meteorological parameters

The most relevant results obtained by modeling the dispersion of pollutant gases from mobile sources using AERMOD in Bahía Blanca's central area, during July 2020–June 2022, are presented in this section. In addition, the average and highest concentration values reached are shown, analyzing both the meteorological and vehicle flow situation. It should be noted that a total of 104 dispersion situations were modeled for each monitored street and peak hours analyzed, totaling 936 modeled cases per contaminant. It is important to take into account that the combination of different percentages per vehicle type segmentation in each street will affect the values of emission rates, as well as the dispersion of these emissions will be affected by meteorological factors. Table 3 presents the data of hourly vehicle flow and maximum emission rates detected among the cases analyzed, as well as the average vehicle flow in peak hours considering all data for the period analyzed. Meanwhile, the maximum concentrations of CO and NOx obtained by dispersion modeling with AERMOD can be observed in Tables 4 and 5.

Table 3 Maximum CO and NOx emission rates and maximum vehicle flow values for each examined intersection. Also, the average traffic flow in peak hours during the analyzed period is detailed

Intersection	Street	Maximum CO emission rate *[g/s·m²]* Date–hour	Maximum NOx emission rate *[g/s·m²]* Date–hour	Maximum traffic flow *[veh/h]* Date–hour	Average traffic flow in peak hours *[veh/h]*
A	Estomba	0.00014897 2021/11/02 Afternoon	0.00003503 2021/11/30 Morning	1380 2021/11/30 Morning	960
	Roca	0.00009553 2021/10/26 Afternoon	0.00002375 2021/10/12 Afternoon	1104 2021/10/12 Afternoon	598
B	Sarmiento	0.00008350 2021/02/17 Midday	0.00001989 2021/11/02 Morning	1206 2020/08/04 Morning	844
	Zelarrayán	0.00010030 2021/12/07 Midday	0.00002001 2022/06/21 Midday	1146 2021/11/09 Midday	747
C	Brown	0.00012966 2022/03/22 Morning	0.00003170 2020/12/09 Midday	2028 2022/04/12 Morning	1268
	Fitz Roy	0.00014595 2022/03/09 Morning	0.00002194 2022/03/09 Morning	1158 2022/03/09 Morning	582

Based on a simple analysis of Tables 3, 4, 5, it can be said that the maximum concentration values are not associated with the same time when the highest levels of traffic flow and emission rates were detected. For example, if we are in the particular case of Sarmiento and Zelarrayán, the maximum concentration values of both pollutants studied are presented in the morning of 2022/05/10 (see Tables 4 and 5), where the vehicle flow over Sarmiento Street was a 11% lower than the maximum (see Table 3) and a 27% higher than the average (see Table 3) while on Zelarrayán Street the flow was a 52% less than maximum and 27% less than the average. Similar analysis could be carried out with emission rates. This situation leads to thinking about the importance of the meteorological factor in modeling. In this regard, the meteorological data detected at the time when the highest concentrations of pollutants were recorded are presented in Table 6. It was detected that the three cases present conditions of a stable atmosphere, which is evidenced with the negative value of the sensitive heat flux and the positive value of Monin–Obukhov length, and by the fact

Table 4 Maximum CO concentrations obtained by dispersion modeling using AERMOD, the respective emission rates used in each case, and the corresponding traffic flow

Intersection	Street	Maximum CO concentration *[μg/m³]* Date–hour	CO emission rate *[g/s·m²]*	Traffic flow *[veh/h]*
A	Estomba	608.30 2022/03/15 Morning	0.00013616	1290
	Roca		0.00004598	642
B	Sarmiento	492.30 2022/05/10 Morning	0.00003459	1068
	Zelarrayán		0.00003228	546
C	Brown	738.85 2022/05/03 Morning	0.00011853	1638
	Fitz Roy		0.00005978	636

Table 5 Maximum NOx concentrations obtained by dispersion modeling using AERMOD, the respective emission rates used in each case, and the corresponding traffic flow

Intersection	Street	Maximum NOx concentration *[μg/m³]* Date–hour	NOx emission rate *[g/s·m²]*	Traffic flow *[veh/h]*
A	Estomba	163.55	0.00003285	1332
	Roca	2022/05/10 Morning	0.00001203	618
B	Sarmiento	232.96	0.00001759	1068
	Zelarrayán	2022/05/10 Morning	0.00001217	546
C	Brown	220.37	0.00002646	1482
	Fitz Roy	2022/05/10 Morning	0.00001608	846

that the parameters of convective velocity, vertical potential temperature gradient above the convective mixing height and convective mixing height, all associated with convective mixing, are not calculated. On the other hand, low wind speed values were detected, which hinders the transport of pollutants. Furthermore, it should be noted that the days in which the peak concentrations were detected correspond to the morning of autumn dates. In this sense, it is important to notice that these meteorological conditions are registered only in the 8% of the autumn days of 2021–2022 (14 days of 184). Finally, Fig. 5 presents the dispersion plots of the pollutant gases analyzed at the emission site (CO and NOx). These graphs show how the gases are dispersed following the shape of the streets, with the highest concentration levels on the street itself and on the surrounding sidewalks.

Table 6 Atmospheric conditions detected at the time when the maximum concentrations of polluting gases were modeled

Meteorological factor	2022/03/15 Morning	2022/05/03 Morning	2022/05/10 Morning
Sensible heat flux [W/m²]	−9.9	−10.5	−11.5
Surface friction velocity [m/s]	0.13	0.15	0.13
Convective velocity scale [m/s]	−9	−9	−9
Vertical potential temperature gradient above convective mixing height [K/m]	−9	−9	−9
Convective mixing height [m]	−999	−999	−999
Mechanical mixing height [m]	724	144	113
Monin–Obukhov length [m]	20.1	31.1	17.4
Surface roughness length [m]	1	1	1
Bowen ratio	2	2	2
Albedo	0.58	1	1
Reference wind speed [m/s] (km/h)	1.5 (5.4)	1.5 (5.4)	1.5 (5.4)
Reference wind direction [degree]	16	356	49
Reference height for winds [m]	10	10	10
Reference temperature [K] (°C)	284.4 (11.25)	277.4 (4.25)	276.4 (3.25)
Reference height for temperature [m]	2	2	2
Precipitation type code	0 = none	0 = none	0 = none
Precipitation amount [mm/h]	0	0	0
Relative humidity [%]	94	93	96
Station pressure [mbar]	1006	1015	1014
Cloud cover [tenths]	4	9	3

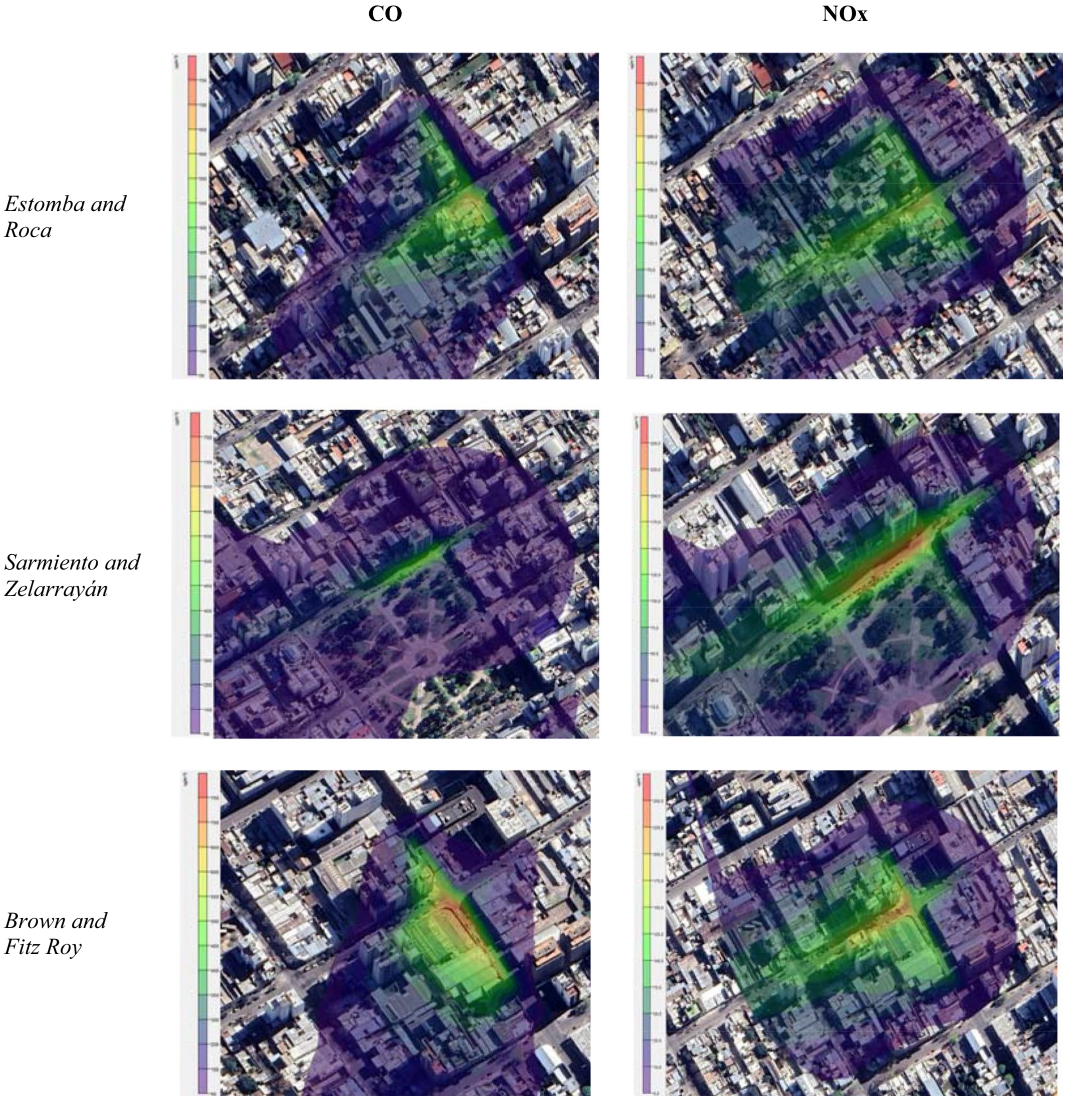

Fig. 5 Dispersion plots of worst-case CO and NOx concentrations at each monitored intersection. The concentration scale is the same for each pollutant in the graphs, allowing quick comparison

It is important to compare the concentration levels modeled with the legislation of Buenos Aires province (Argentina), which is in force in Bahía Blanca, to assess the air quality at peak hours at the monitored points of the city's downtown. The Decree 1074/2018 is the one that establishes the current regulatory framework, establishing implementation stages since 2018. Accordingly, from October 2020, the hourly average limit values for concentration would be 40,000 μg/m^3 for CO and 320 μg/m^3 for NO_2. Meanwhile, as of October 2021, they would be the following: 40,000 μg/m^3 for CO and 288 μg/m^3 for NO_2 and, lastly, from October 2022 the limits were set at 40,000 μg/m^3 for CO, and 188 μg/m^3 for NO_2.

Regarding carbon monoxide, it can be said that in none of the three monitored points, the values are above the permissible legal limits (40,000 μg/m^3); on the contrary, they are well below. The maximum detected values were 608.30 μg/m^3 in Estomba and Roca, 492.30 μg/m^3 in Sarmiento and Zelarrayán, and 738.85 μg/m^3 in Brown and Fitz Roy, values well below the limit of 40,000 μg/m^3 established by the

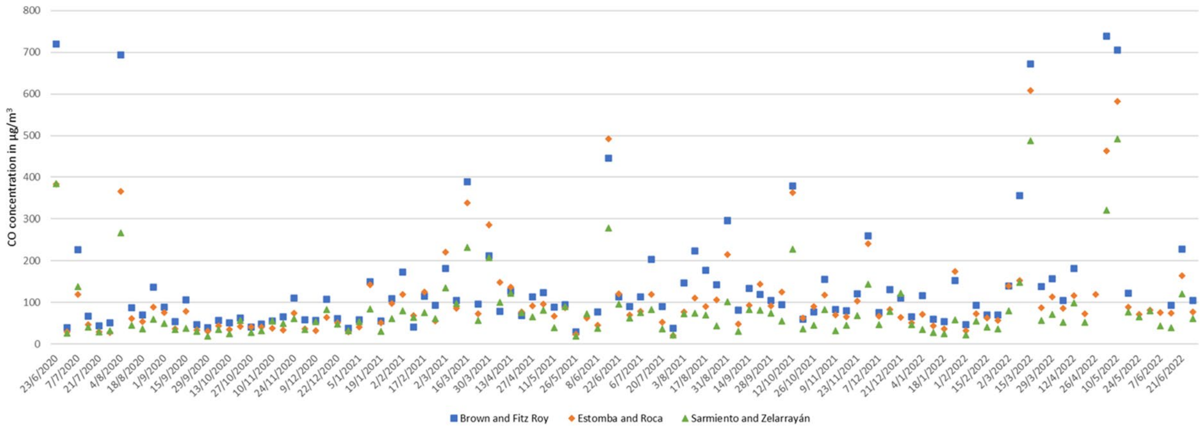

Fig. 6 Evolution of modeled CO concentrations over the study period in the morning peak hour for the three intersections of the downtown area analyzed

regulation. On the other hand, no modeled CO values exceeding the maximum value of 35,000 µg/m^3 recommended by the World Health Organization are detected (WHO, 2024). Regarding the comparison of CO results with the international AQI standard (US-EPA-2018), nothing can be concluded with accuracy since the modeling is performed on a 1-h average and the AQI values are given on an 8-h average. However, the modeled CO values, on 1-h average, do not exceed the minimum range of the limits set by the AQI categories on 8-h average. In this sense, it could be inferred that in no case alarms have been generated for the population health. Figures 6, 7, and 8 show the evolution of the modeled CO concentration during the three peak hours analyzed.

On the other hand, the case of NOx is particular because the regulation sets limit values only for NO_2. At this point, it should be remembered that the reactivity of NOx is complex in the atmosphere. In this respect, it is difficult to establish the gradients of NO, NO_2, and NOx, since they change dynamically in areas near the streets; in turn, these gradients are influenced by the available sunlight, ozone, and other compounds (Richmond-Bryant et al., 2018). In this sense, a tier 1 approach is followed in which a complete conversion of all nitrogen oxides (NOx) into nitrogen dioxide (NO_2) is assumed; i.e., the obtained NOx value is taken as the final value of NO_2 (US-EPA, 2020). In particular, if the abovementioned stages of the local law are considered, the limit value

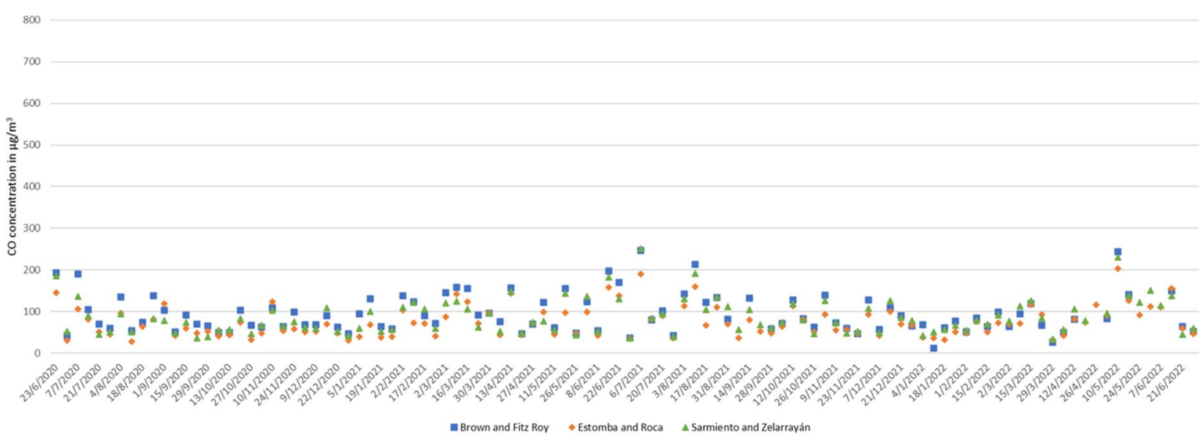

Fig. 7 Evolution of modeled CO concentrations over the study period in the midday peak hour for the three intersections of the downtown area analyzed

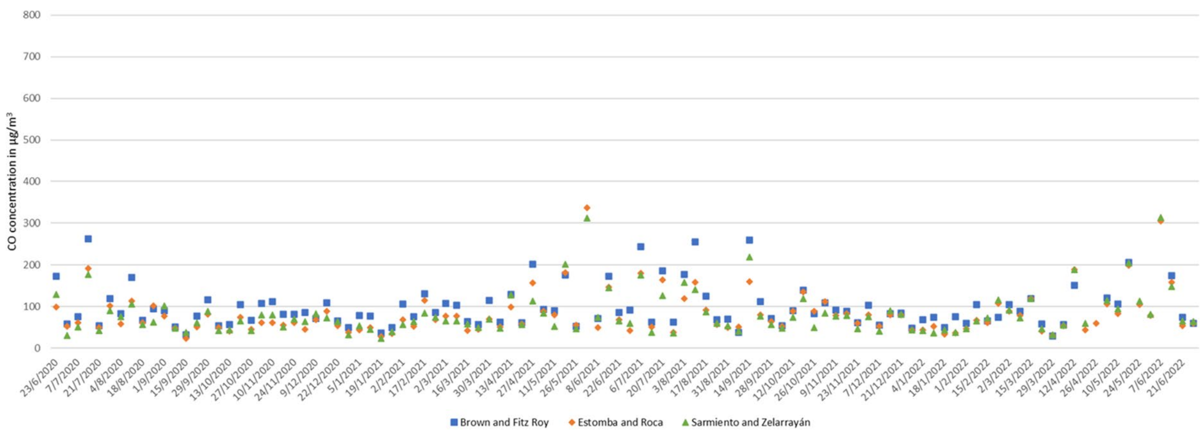

Fig. 8 Evolution of modeled CO concentrations over the study period in the afternoon peak hour for the three intersections of the downtown area analyzed

for NO_2 would be 288 μg/m^3 during the period under studied, being this threshold not reached in any of the monitored situations. However, if we consider the stage that began in October 2022, it is detected that the limit value of 188 μg/m^3 is exceeded in two of the analyzed intersections. Given this situation, it is found that there are only four times when the modeled NOx levels are above the limit allowed according to the third stage of the current legislation. Figures 9, 10, and 11 present the NOx results obtained from all the modeling, disaggregated by intersection in the morning, midday, and afternoon peak hour, where the four points that exceed the established legal limit can be quickly observed in morning hours. It should be considered that at the intersection of Estomba and Roca streets, the limit is not exceeded at any time analyzed in this work, while at the intersection of Sarmiento and Zelarrayán only one episode is detected where the limit value is exceeded, which is the maximum value of NOx throughout the period analyzed. Meanwhile, at the corner of Brown and Fitz Roy, three moments are detected in which the modeled NOx concentrations would exceed the limit set according to the most rigorous stage of the legislation. The three events at Brown and Fitz Roy streets represent only 0.96% of the 312 times analyzed at that intersection (104 days

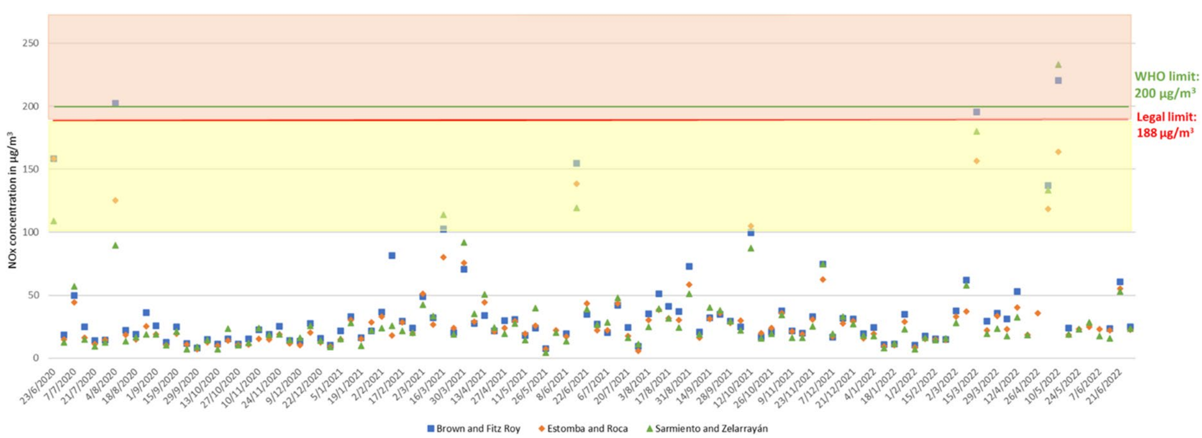

Fig. 9 Evolution of modeled NOx concentrations over the study period in the morning peak hour for the three intersections of the downtown area analyzed. The limit values established by the third phase of the local law (red line) and by the WHO (green line) are included. The AQI classification is also shown, shaded yellow (moderate, 101–188 [μg/m^3]), shaded orange (unhealthy for sensitive groups, 189–677 [μg/m.^{3}])

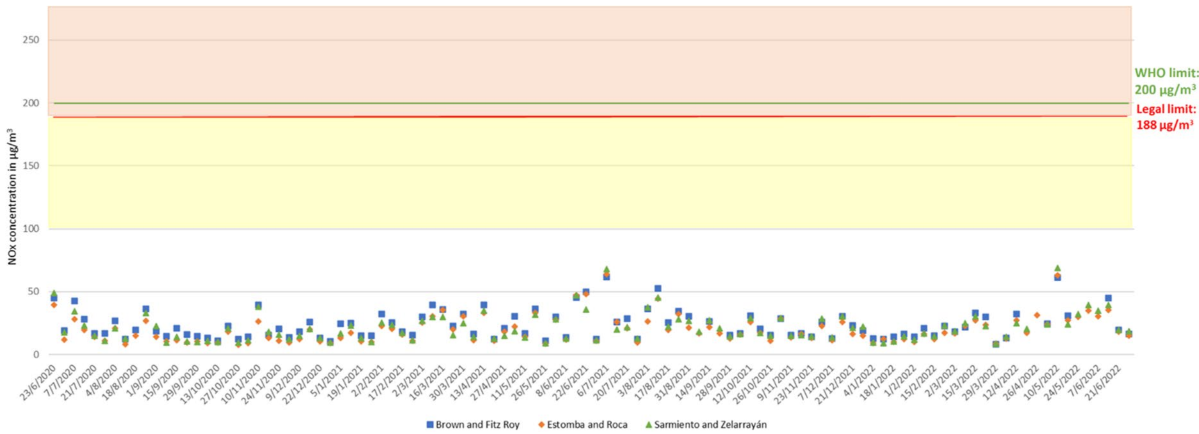

Fig. 10 Evolution of modeled NOx concentrations over the study period in the midday peak hour for the three intersections of the downtown area analyzed. The limit values established by the third phase of the local law (red line) and by the WHO (green line) are included. The AQI classification is also shown, shaded yellow (moderate, 101–188 [μg/m^3]), shaded orange (unhealthy for sensitive groups, 189–677 [μg/m.^{3}])

in three peak hours), while the case reported at the intersection of Sarmiento and Zelarrayán is equivalent to 0.32% of the total of 312 modeled events at that intersection. In short, of the 936 NOx modeled cases, the four episodes that exceed the current legal limit represent only 0.4% of the total. Also, it has been detected that these cases occurred with the worst meteorological conditions (stable atmospheric stability and low wind speed) that are registered only in the 8% of the autumn days of 2021–2022. On the other hand, if the limit advised by the WHO for NO_2 in an hourly average (200 μg/m^3) is considered, it would only be exceeded in three moments during the 2 years analyzed, two at the intersection of Brown and Fitz Roy and one at Sarmiento and Zelarrayán.

In the case of the comparison between the NOx modeling results (considered entirely as NO_2) and the AQI standards (US-EPA, 2018), it is detected that the four NOx episodes that exceed the legal limit would generate orange alarm situations (see Fig. 9), in which it is recommended that asthmatic individuals, children, and elderly people limit prolonged efforts,

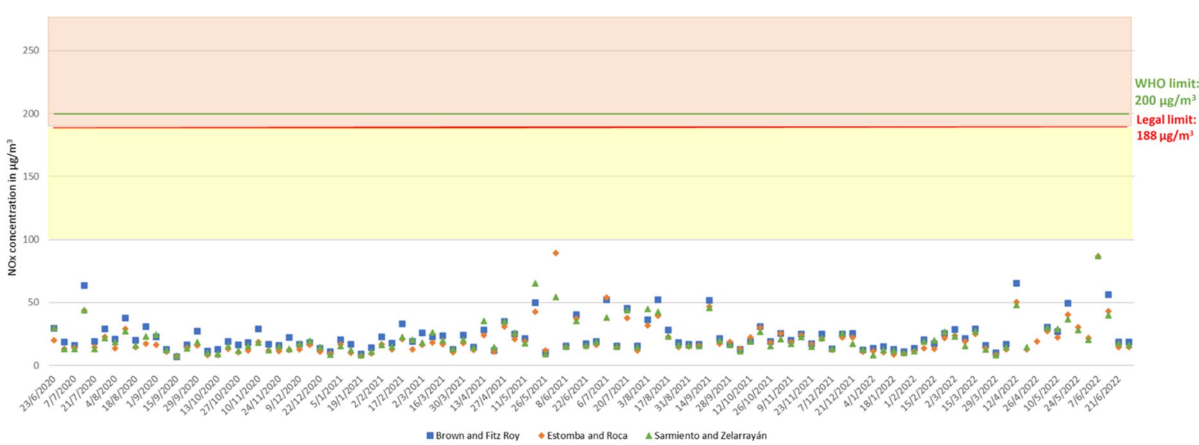

Fig. 11 Evolution of modeled NOx concentrations over the study period in the afternoon peak hour for the three intersections of the downtown area analyzed. The limit values established by the third phase of the local law (red line) and by the WHO (green line) are included. The AQI classification is also shown, shaded yellow (moderate, 101–188 [μg/m^3]), shaded orange (unhealthy for sensitive groups, 189–677 [μg/m.^{3}])

especially near streets with heavy traffic. In addition, it should be noted that 16 episodes have been found in which the AQI would be in terms of moderate (yellow) out of a total of 936 modeled cases, being four at the intersection of Brown and Fitz Roy, five in Sarmiento and Zelarrayán, and seven in Estomba and Roca (see Fig. 9). Although the current legal limit is not exceeded at these times, it is recommended that sensitive people try not to make efforts mainly near busy streets.

At this point, it is interesting to highlight what was reported in another Argentine city such as Córdoba Capital where Mateos et al. (2018) presents that the mean NO_2 exceeds the limit of 100 ppb (188 μg/m^3) in areas with high vehicular traffic studied in all seasons of the year, in contrast to Bahía Blanca where only in some autumn morning high values were observed. On the other hand, when we compare our results to those presented in the literature (see Table 7), we notice that our results are well below the maximum modeled in large city streets such as Muscat, Oman (Amoatey et al., 2020), and Ibadan, Nigeria (Odediran et al., 2024). In the case of CO, our results are 94% and 99% lower than those reported for both cities, respectively, while our maximum NOx concentration is 82% and 99% lower in our case. In the study presented for a Brazilian high vehicular flow avenue (Macêdo & Ramos, 2020), the CO concentration cannot be directly compared since, in Brazil, it was modeled in 8 h average while in this work it was done in 1 h average. Regarding NOx, it can be said that the level reported in Brazil doubles the maximum value detected in Bahía Blanca.

According to the analysis so far, it could be inferred that the air quality of the Bahía Blanca microcenter due to the two pollutants tested (CO and NOx), over the 2 years studied, would not be serious from the point of view of health effects. The current legal limit is only exceeded in 0.4% of the total cases modeled for NOx in 2 years, while in 2% of the episodes (20 out of 936), health recommendations would be presented, and these are only directed to sensitive groups.

Analysis of alternative future scenarios

This section presents the results of the scenario analysis, considering the worst-case scenario in terms of air quality levels, and proposes two alternatives in order to reduce them. The scenario analysis is generally associated with a methodology where predictions or forecasts are formulated and analyzed, in order to identify how they would impact on a real scenario. Also, it involves describing a future that question current assumptions and describe the situation in a given time period (Duinker & Greig, 2007; Tourki et al., 2013). This technique helps in evidence-based decision making by framing future alternatives that support current and future needs, associated with the potential city growth in line with the transportation of petroleum products for export through the port (as presented in the "Introduction" section).

So far, considering the entire studied period, the worst-case scenario conditions for air quality levels could be determined by combining the maximum emission rates, presented in Table 3, with the meteorological conditions prevailing in the autumn mornings with low wind, shown in Table 6. While this scenario appears to be the worst that could be configured with the data collected, it would not be

Table 7 Comparison of maximum CO and NOx concentration values between Bahía Blanca, Argentina, and other worldwide cities. The average vehicle flow and population of each city are included

City	Average maximum values of CO *[μg/m^3]*	Average maximum values of NOx *[μg/m^3]*	Average vehicle flow per street *[veh/h]*	Population	Reference
Bahía Blanca, Argentina	613.15	205.63	976	335,190	
Aracajú, Brazil	27,560.00*	550.00**	3000	641,523	Macêdo & Ramos, 2020
Muscat, Omán	10,211.21	1130.98	1138	1,500,000	Amoatey et al., 2020
Ibadan, Nigeria	347,379.27	54,353.52**	5646	3,800,000	Odediran et al., 2024

*On average 8 h

**NO_2 modeled

Table 8 Emission rates and concentrations obtained by modeling for NOx in scenario 1

	Estomba and Roca		Sarmiento and Zelarrayán		Brown and Fitz Roy	
SCENARIO 1	Estomba	Roca	Sarmiento	Zelarrayán	Brown	Fitz Roy
NOx emission rate [g/s·m^2]	0.00003505	0.00002333	0.00001989	0.00001604	0.00003061	0.00002194
NOx concentration [µg/m^3]	238.44		272.75		277.87	

the most realistic since the maximum emission rates are distributed between the three different peak hours analyzed. In this sense, we will continue with the approach of more realistic scenarios, for which the same meteorology is considered, determined by the morning of 2022/05/10 presented in Table 6. Scenario 1 considers the maximum emission rates detected in the morning hours, since that time of the day has presented the maximum concentration values. In addition, only NOx modeling is considered in this analysis, because it was the pollutant whose concentration exceeded the limits permitted by law at some point. Table 8 shows the emission rates and the modeling results for scenario 1. Meanwhile, Table 9 contains the details of the vehicle flow segmentation of scenario 1. Mainly in scenario 1, considering a tier 1 approach (full conversion of NOx to NO_2), the threshold related to nitrogen oxides is exceeded at the three analyzed intersections. In scenario 1, the intersection that most exceeded the 188 µg/m^3 limit was Brown and Fitz Roy (by 48%), followed by Sarmiento and Zelarrayán (45%) and Estomba and Roca (27%).

Based on the above, it is proposed to analyze two possible scenarios, which have a more sustainable approach considering emissions reduction. In this regard, the aim is to promote active mobility and public transport. The establishment of scenario 2 and scenario 3 guidelines should be considered to be based

Table 9 Segmentation of vehicle flow in scenario 1 for each street, considering maximum NOx emission rates in the morning hours only

Vehicle type	Fuel	Standard	Estomba *[veh/h]* 2021/11/30	Roca *[veh/h]* 2021/10/05	Sarmiento *[veh/h]* 2021/11/02	Zelarrayán *[veh/h]* 2022/03/09	Brown *[veh/h]* 2022/04/05	Fitz Roy *[veh/h]* 2022/03/09
MC	Gasoline	EURO I	144	108	42	132	180	222
Car	Gasoline	Pre-EURO	12	10	9	9	17	10
		EURO I–IV	382	326	295	266	540	317
		EURO V	139	119	108	97	197	116
	Diesel	Pre-EURO	8	7	6	6	11	7
		EURO I–IV	253	216	195	176	357	210
		EURO V	92	79	71	64	131	77
	CNG	Pre-EURO	3	3	2	2	5	3
		EURO I–IV	100	85	77	69	141	83
		EURO V	36	31	28	25	52	30
Pick-up	Diesel	Pre-EURO	4	3	6	1	5	2
		EURO I–IV	71	51	115	24	98	34
		EURO V	51	36	82	17	70	24
LCV	Diesel	Pre-EURO	2	0	1	0	2	0
		EURO I–IV	32	4	20	12	39	8
		EURO V	14	2	10	6	18	4
Bus	Diesel	Pre-EURO	0	0	0	0	0	0
		EURO I–IV	31	16	26	26	37	10
		EURO V	5	2	4	4	5	2

on the number of vehicles in scenario 1. Based on this, scenario 2 proposes a 25% reduction of motorcycles, diesel pick-up trucks, and diesel cars, as well as restricting the access into the downtown area to vehicles considered prior to the implementation of EURO standards, and increasing the frequency of public transport by 25%. Based on this description, the resulting vehicle flow segmentation for scenario 2 is presented in Table 10.

On the other hand, scenario 3 presents the implementation of a low emission zone (LEZ) in the city's downtown area as medium-sized Spanish cities do. For this purpose, vehicles are categorized using an environmental wafer system (Vega & Sanz, 2021). In this sense, environmental labels are classified in:

- *0*: motorcycles, tricycles, quad, cars, light vans, vehicles with more than eight seats and freight vehicles; classified as battery-powered, extended-range electric vehicles, plug-in hybrid vehicles with a minimum range of 40 km or fuel cell vehicles.
- *ECO*: plug-in hybrid vehicles with a range of less than forty kilometers, non-plug hybrids, natural gas vehicles (CNG and LNG), liquefied petroleum gas vehicles. It should be clarified that in all these cases the criteria of label C must be met.
- *C*: EURO 6/VI diesel cars and light commercial vehicles; EURO 4/IV, 5/V, or 6/VI gasoline cars or light commercial cars; EURO 3 or 4 motorcycles or vehicles with more than 8 seats and EURO 6/IV freight transport.
- *B*: EURO 4/IV or 5/V diesel cars and light commercial vehicles, EURO 3/III gasoline cars or light commercial cars, EURO 2 motorcycles, or vehicles with more than 8 seats, and EURO 4/VI or 5/V freight transport.
- The rest of the vehicles are included in environmental category *A* but do not have a distinctive (label).

Vehicles with *0*, *ECO*, *C*, or *B* labels are the ones that can usually enter the LEZ. In the case of scenario 3, the four categories will be considered; however, it should be noted that the *0* and *ECO* segments are not represented within the vehicle fleet of Bahia Blanca analyzed in this study because they are emerging categories and their percentage of participation is very low. On the other hand, we must take into account that in this study all motorcycles are considered to follow a EURO I standard. According to Resolution 42/2018 for approximately April 2020, "all existing models of motorcycles that are commercialized, manufactured and/or imported in the territory of the Argentine Republic should comply with EURO II standards" (BOA, 2018). However, Resolution 460/2019 postponed the calendar for 24 months, so that in April 2022 EURO II standard would be mandatory for motorcycles (BOA, 2019). Finally, Resolution 14/2023

Table 10 Segmentation of vehicle flow in scenario 2, based on the segmentation of vehicle flows from scenario 1 (see Table 7)

Vehicle type	Fuel	Standard	Estomba *[veh/h]*	Roca *[veh/h]*	Sarmiento *[veh/h]*	Zelarrayán *[veh/h]*	Brown *[veh/h]*	Fitz Roy *[veh/h]*
MC	Gasoline	EURO I	108	81	32	99	135	167
Car	Gasoline	EURO I–IV	382	326	295	266	540	317
		EURO V	139	119	108	97	197	116
	Diesel	EURO I–IV	190	162	146	132	268	158
		EURO V	69	59	53	48	98	58
	CNG	EURO I–IV	100	85	77	69	141	83
		EURO V	36	31	28	25	52	30
Pick-up	Diesel	EURO I–IV	53	38	86	18	74	26
		EURO V	38	27	62	13	53	18
LCV	Diesel	EURO I–IV	32	4	20	12	39	8
		EURO V	14	2	10	6	18	4
Bus	Diesel	EURO I–IV	39	20	33	33	46	13
		EURO V	6	3	5	5	6	3

Table 11 Segmentation of vehicle flow in scenario 3, based on the segmentation of vehicle flows from scenario 1 (see Table 7)

Vehicle type	Fuel	Standard	Estomba *[veh/h]*	Roca *[veh/h]*	Sarmiento *[veh/h]*	Zelarrayán *[veh/h]*	Brown *[veh/h]*	Fitz Roy *[veh/h]*
Car	Gasoline	EURO III–IV	241	205	186	168	340	200
		EURO V	139	119	108	97	197	116
	Diesel	EURO IV	129	110	99	90	182	107
		EURO V	92	79	71	64	131	77
	CNG	EURO III–IV	63	54	49	43	89	52
		EURO V	36	31	28	25	52	30
Pick-up	Diesel	EURO IV	36	26	59	12	50	17
		EURO V	51	36	82	17	70	24
LCV	Diesel	EURO IV	16	2	10	6	20	4
		EURO V	14	2	10	6	18	4
Bus	Diesel	EURO III–IV	31	16	26	26	37	10
		EURO V	5	2	4	4	5	2

presents a new schedule for the implementation of each EURO standard in motorcycles (BOA, 2023). Based on the above, it could be considered that no motorcycle could circulate through the LEZ during the period studied in this work, which ends in June 2022. On the other hand, it is considered that all urban buses can travel through the LEZ, considering that these vehicles are less than 10 years old and the intention to encourage the use of the public transport. The resulting data on the vehicle flow segmentation for scenario 3 is detailed in Table 11. According to the information generated by the emissions inventory for 2018, presented in Grassi et al., 2021, it can be said that in the case of this scenario, gasoline and CNG cars represent 63% of those in the EURO I–IV segment of the scenario 1, while, all those diesel vehicles, excluding busses, account for 51% of those of the EURO I–IV segment of scenario 1.

Table 12 shows the emission rates and modeled concentrations for each intersection analyzed, for both scenarios 2 and 3. By analyzing the obtained results for scenario 2, it can be seen that the emission rate was reduced by an average of 13% compared with scenario 1, due to the decrease in vehicle flow in the area studied. Also, the NOx modeled concentration decreased by 13% on average, compared to scenario 1. It should be noted that the NOx levels modeled in this scenario, analyzed from a tier 1 approach, continue to be above the maximum concentration permitted by law (presented in bold in Table 12). Regarding the analysis of the scenario 3 results, it can be said that NOx emission rates were reduced by 34% on average, due to the decrease of the vehicle flow, mainly associated with the reduction of old diesel cars and light vehicles. Meanwhile, the NOx concentration modeled decreases by 34% on average, compared to that obtained in scenario 1. In the

Table 12 Emission rates and concentrations obtained by modeling for NOx in scenarios 2 and 3. Values exceeding the legal limit are highlighted in bold

	Estomba and Roca		Sarmiento and Zelarrayán		Brown and Fitz Roy	
SCENARIO 2	Estomba	Roca	Sarmiento	Zelarrayán	Brown	Fitz Roy
NOx emission rate [g/s·m²]	0.00003196	0.00002024	0.00001811	0.00001527	0.00002729	0.00001709
NOx concentration [µg/m³]	**210.50**		**251.07**		**230.76**	
SCENARIO 3	Estomba	Roca	Sarmiento	Zelarrayán	Brown	Fitz Roy
NOx emission rate [g/s·m²]	0.00002388	0.00001500	0.00001421	0.00001115	0.00002051	0.00001218
NOx concentration [µg/m³]	156.50		**193.59**		168.86	

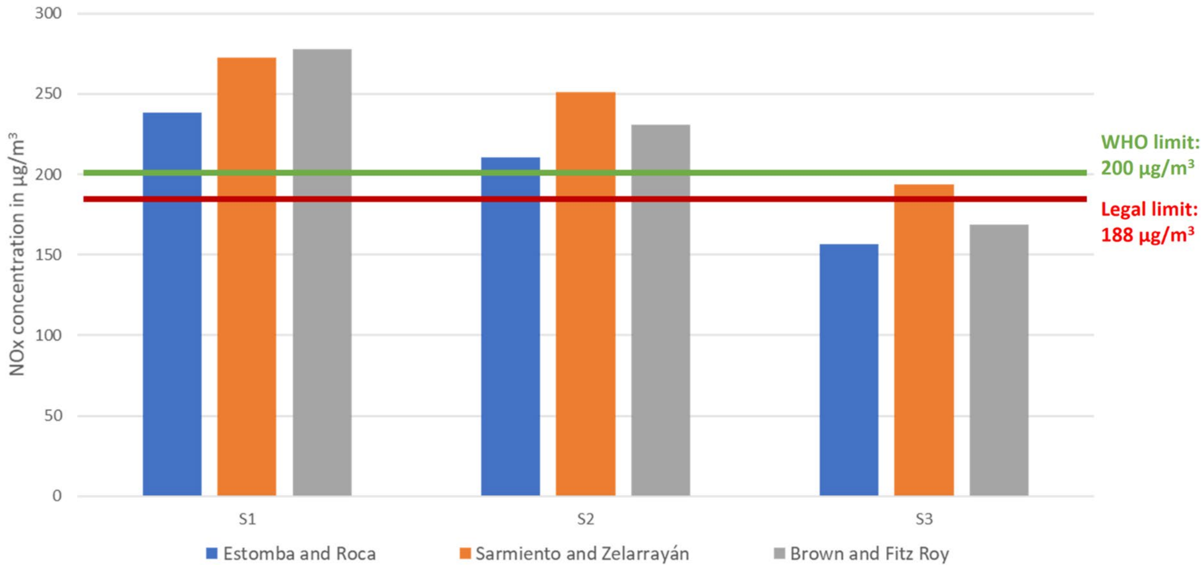

Fig. 12 Comparison of modeled NOx concentrations in each scenario for each intersection analyzed

case of this scenario 3, only the intersection of Sarmiento and Zelarrayán presents a maximum concentration slightly (3%) above the maximum allowed by legislation.

In this regard, the analysis of scenarios allows to evaluate alternatives to the city's current vehicle fleet in order to reduce its emissions and improve air quality. It is interesting to mention that in scenarios 2 and 3, the NOx emission rates were reduced by an average of 12% and 34%, respectively, as the number of vehicles circulating in the area studied decreased with respect to scenario 1. Meanwhile, the NOx concentration due to the dispersion effect, as expected, decreased with respect to the results of scenario 1 in the same proportion as the emission rates. Although the scenarios 2 and 3 considered alternative variables, both show that NOx concentrations remain above the permitted limit at some analyzed points of the downtown area (see Fig. 12). In any case, it should not be forgotten that the meteorological condition used was the worst detected in the analysis that includes a 2-year period and these extreme situations (autumn mornings with stable atmospheric stability and low wind speed) only represented the 8% of the autumn days of 2021–2022. However, it could happen, and considering the promotion of more sustainable mobility alternatives can mitigate those few critical moments. In this sense, we highlight the importance of continuing to monitor critical periods such as autumn mornings, in order to evaluate and propose temporary alternatives for these situations, such as reducing the flow of diesel LCV and private vehicles. It is important to note that reaching a balanced and sustainable urban mobility is not achieved by imposition or strict regulation, but rather it is necessary to positively motivate citizens and create consensus (Foltýnová et al., 2021). It is also necessary to ensure proper and continuous road safety education through time. Finally, it should be noted that these scenarios do not analyze the problem of vehicular congestion, which is foreseen as future work through traffic simulations.

Conclusions

This paper presented the results obtained from the air pollution dispersion modeling (AERMOD) generated by mobile sources in the downtown area of Bahía Blanca city (Argentina). It was detected that the maximum concentration values at each of the studied points occurred in the morning hours of autumn days, particularly when stable atmospheric conditions and low wind speed values were presented. It is interesting to note that the maximum concentration values detected are not directly associated with maximum levels of vehicle flow or emission rates, which highlights the importance of meteorological parameters in the modeling. On the other hand, as for the comparison with the current legislation, it is concluded that the limits for CO have not been exceeded at any time. Regarding NOx levels, four moments are detected in which the maximum levels are exceeded in two of the three intersections studied, considering a tier 1 approach in which all NOx is considered NO_2. At this point, it should be noted that the maximum concentration values detected have only occurred on a few occasions in the total of modeling performed, representing 0.4% of the total amount of modeling situations (4 of 936 total cases analyzed). In addition, according to the analysis based on the AQI, only 2% of the episodes (20 out of 936) would be presenting health recommendations, and these are only directed to sensitive groups. Therefore, it could be inferred that, based on all the results of two full years of modeling, the air quality of the microcenter of the city would not be presenting situations of serious health compromise in reference to CO and NOx due to vehicular traffic.

On the other hand, the scenario study allows an analysis of hypothetical cases corresponding to the downtown area of the city of Bahía Blanca, with the aim of analyzing potential improvements in the urban traffic which collaborate with the reduction of air pollutant levels. From the analysis of the scenarios, it can be concluded that diesel vehicles have an influence on NOx emissions. In this sense, only in scenario 3, where a LEZ restricting the access of old diesel vehicles (prior to EURO 4) is implemented, almost all NOx concentration values are below the values established by law. In any case, it should be remembered that we worked with the worst meteorological scenario recorded during the studied period which appears only in the 8% of autumn morning of 2021–2022. In this regard, it is considered that planning alternatives that could be implemented temporarily would be more convenient than a restriction as strict as the one proposed by the LEZ. In addition, we would like to emphasize that when planning a redesign of public space and urban mobility, it is important to focus first on educating and motivating citizens to use transportation in a more efficient way, considering the three aspects of sustainability: environmental, social, and economic. It is worth mentioning that sustainable mobility has an impact not only on air pollution, but also on noise pollution, traffic congestion, and road accidents, among others. In particular, citizen participation is essential to ensure the success of any urban mobility planning.

Last but not least, the conclusions of this study are specific to the study area, as only streets of the city's downtown area have been analyzed. Finally, we consider that our contribution will serve to compare and assess urban air quality trends with other medium-sized Latin American cities. It will also be useful for local decision-making on future interventions to mitigate the consequences of vehicle fleet growth due to a possible expansion of the city in the coming years.

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Data availability We do not have any research data outside the submitted manuscript file.

Declarations

Ethical responsibilities of authors All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

Consent to participate Not applicable.

Consent for publication Not applicable.

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