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Environmental inequalities in the municipality of Lisbon: spatial analysis of combustion gases

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Abstract

Some inducing factors of climate change can be attributed to a set of pollution indicators, and the territorial distribution of pollution has repercussions on environmental inequalities. Based on the case study of Lisbon, we map some environmental inequalities and how they relate to the location of transport infrastructures, green spaces, and mobility practices. How is air pollution distributed inside Lisbon? What is the relationship between the distribution of air pollution and the location of transport infrastructure, and green spaces? The results show that there are environmental inequalities, air pollution is higher in zones with a dense road network and heavy traffic. Environmentally friendly mobility practices do not exclude an exposure to higher levels of air pollution due to combustion gases, representing a mismatch between the production of pollution and environmental exposure.

Keywords: Climate change; environmental inequalities; means of transport; mobility practices; data science; public policies.

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1. Introduction

After the Paris Agreement (EC, 2015), there was an environmental paradigm shift, recognizing that only with the contribution of all it will be possible to prevent climate change and limit the planet's global warming to 1.5ºC above pre-industrial levels. A series of strategic packages emerged to answer this global challenge, one of which is directly related to decarbonizing the transport sector, named the Clean Mobility Package (EC, 2018). To comply with the Paris Agreement, the European Commission (EC) presented the legislative package "Clean Energy for all Europeans" to

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promote the energy transition between 2021 and 2030. Portugal submitted the Integrated National Energy and Climate Plan (NECP) to the EC, where ambitious targets were set. Mobility and transport decarbonization assume a particular focus since it is one of the most critical sectors in terms of national Greenhouse gas (GHG) emissions. The NECP establishes sectoral targets for reducing GHG emissions, by reference to the emissions recorded in 2005. It is planned that these emissions will be reduced by 40% in the transport sector. The NECP sets a target of 20% for using renewable energy in the transport sector by 2030. In order to achieve this goal, a significant increase in electric vehicles is expected. Although these strategies have been established, it remains fundamental to continue analysing the environmental parameters to characterize pollution and how it is affecting the people. Environmental pollution, particularly air pollution, is one of the most significant health risks. According to the World Health Organization (WHO, 2021a), reducing air pollution levels will reduce the number of cardiovascular problems, lung cancer, and other respiratory diseases, namely asthma. It is essential to address these risk factors to protect public health.

Our study aims to characterize air pollution due to combustion gases from any source and to assess environmental inequalities in the municipality of Lisbon, using metadata. To such an end, Lisbon was assessed in terms of pollution indicators, considering data provided by monitoring stations, made available on the 'Lisboa Aberta' webpage (CML, 2022). Carbon Monoxide (CO) and Nitrogen Dioxide (NO_2) were evaluated in the municipality of Lisbon.

Anthropogenic CO is produced mainly from the incomplete combustion of fossil fuels. In urban areas, car traffic is the primary source of CO, being the areas of heavy traffic higher concentrations of this pollutant. The traffic conditions influence its concentrations, as CO emissions are inversely proportional to circulation speed.

NO_2 is produced in combustion processes, such as industrial, commercial, residential combustion and road or maritime transport (combustion engines). Furthermore, in the chemical industry, manufacturing processes involving nitrogen, such as producing nitrogen fertilizers, can produce nitrogen oxide. In urban areas, such as Lisbon, it is expected that transport is the main source of this pollutant. High levels of traffic will be responsible for high NO_2 concentrations, which follow variations in car traffic. Our study analyses the distribution of some air pollution parameters across the municipality of Lisbon, allowing the visualization of the most environmentally exposed areas. These environmental inequalities are then compared with the location of green spaces and transport infrastructures, namely the road and cycle networks, and the public transport system. It is then possible to relate the location and the use of different types of transport with the production and exposure to pollution.

2. The state of art

Scientific research has shown that social inequality is associated with climate change and cities are decisive spaces to reverse the current environmental impacts (OECD, 2021). The most severe effects of urban pollution can be mitigated through sustainable lifestyles, practices and policies, that should be associated with the different transport and mobility practices found in major cities (Curtis et al. 2019; Giannotti et al. 2021). Science has proven that exposure to pollution has a harmful effect on human health (WHO, 2019; Spychała et al., 2020). This means that environmental inequalities have an impact on a set of indicators of health and disease, life and death, named vital inequalities. According to a study by the WHO's International Agency for Research on Cancer (WHO, 2021b), outdoor air pollution is directly correlated with carcinogenic diseases, with particulate matter (PM) being the most associated with increased cancer incidence, especially lung cancer.

Social inequalities are one of the main factors of climate change and environmental inequalities, mostly related with the global wealth and income distribution, which causes differentiated levels of pollution (Chancel, 2020), and consequently spatial injustice in the urban areas and cities around the world. Social inequalities mediate the capacity to combat and prevent the effects generated by equal levels of environmental exposure (WHO, 2019; Saex and López-Casasnovas, 2019; WHO, 2010). More favoured social categories have a greater capacity to combat the harmful effects on health resulting from exposure to environmental pollution. Inversely, the most disadvantaged social categories are less able to combat the harmful effects on health created by environmental pollution. Moreover, since the health status of individuals may impact their labour productivity and the capacity to find or keep a job, environmental inequalities may have a much wider impact on social inequalities, even if indirectly, rather than just on the health. We contribute to unveiling and mapping environmental inequalities and behaviours, the usage of different kinds of transport (Kemp et al. 2016, Ferreira et al. 2021) and mobility patterns, matching them with the transport supply network and the several urban infrastructures of soil occupation in the municipality of Lisbon. Without this mapping and relational intertwining, it will not be possible to conceive and evaluate the best environmental policies for the cities. The results of our research help to achieve an integrated approach of the 2030 UN Agenda for the local sustainable development goal (SDG 13) regarding the municipality of Lisbon, a decisive tool for building a more inclusive society, contributing to reducing unsustainable inequalities and to combating the impacts of climate change (Sachs et al., 2019).

3. Methods

3.1. Data description

The data used to study the pollution levels in Lisbon is available in Portal Lisboa Aberta (CML, 2022). This portal monitors pollution and environment parameters in key areas of the municipality, using sensors spread by 80 locations. Each sensor collects measurements hourly, and each measurement is the average of all measurements within that hour. The pollution indicators chosen for our study are the following air quality parameters: CO (measured in mg/m^3) and NO_2 (measured in μg/m^3). These two were selected because they reflect typical pollution metrics about transportation and mobility.

3.2. Data Reading

The datasets were stored on different json files, each file containing measurements of the specific parameter and location. Since two parameters were selected, and there are 80 locations with sensors, 160 files were downloaded, via URLs. To automate this process, a script that generates all the link combinations was created. After downloading the data, a merge of the files by parameter was carried out, giving rise to two json files, each containing measurements of the specific parameter in all the locations. The next section explains the process of data cleaning applied to these two databases.

3.3. Data Cleaning

The full dataset is composed of 11456602 observations, of which 30006 are not available (NA) values, representing 26% of all the data (table 1). These missing values are encoded as –99 and were removed from the dataset. Some sensor locations store the measurements multiple times, causing many duplicate observations, all of these were deleted from the dataset, since they do not represent a gain of information. Our study focuses on the period between 15-07-2021 and 28-02-2022, given that outside this period the data presents inconsistencies. There is no data prior to the period under analysis, as this specific sensor network was installed in 2021. Thus, it is not possible to compare the sample of the research with former historic sensor data. All negative values in these two variables were removed, given that negative measurements do not make sense in this context.

Table 1. Parameter information.

Parameter	Size	Missing Values %	Duplicates %	Num. sensors	Outliers %
Carbon Monoxide	7408385	0	83.64	66	15.85
Nitrogen Dioxide	4048217	74	86.10	72	0.01
All	11456602	26	84.51	211	3.56

To find the outliers, boxplots and histograms were generated for each parameter. For both parameters, the following method to identify outliers was used: 1) Calculate the first (Q1) and third (Q3) quartiles; 2) Calculate the interquartile range (IQR); 3) Remove measurements < Q1 – margin * IQR; 4) Remove measurements > Q3 + margin * IQR. Fig. 1 shows a boxplot and a histogram of NO_2, before and after the removal of the outliers.

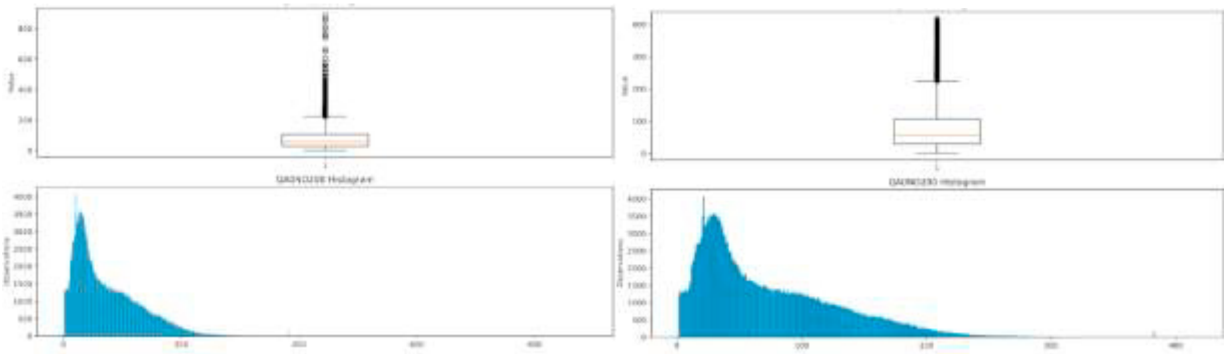

Fig. 1. Boxplot and histogram of NO_2 before (left) and after the outliers' removal (right).

3.4. Data Modelling

The sensors allow knowing how the parameters behave locally, but to have a macro picture of these parameters in the municipality of Lisbon, it is needed to interpolate points all along its limits. To do this, for each parameter, we calculated the average pollution level on each sensor. Using these calculated data points, it was possible to predict all other points of the municipality. This prediction can be done following different approaches, in this study two different approaches were applied: K-Nearest Neighbours (KNN) method and the Inverse Weighted Distance (IWD). The IWD approach was preferred over the KNN, because it presents smoother predictions. This method, as the name states, calculates, for each point an average weighted by the distance squared to a value p, which is the importance given to the distance. The greater the p, the greater the importance given to the distance, our interpolation used $p = 4$. To evaluate how the CO and the NO_2 levels are spread around the municipality of Lisbon, two raster files (i.e., pixel cells with predicted and actual values) were produced using the QGIS software.

3.5. Data Analysis

To understand how and why the pollution levels map across the municipality, a spatial analysis was carried out. First, a map of Lisbon infrastructures (Fig. 2) was created. Secondly, a map of the pollution levels overlapped with Lisbon's Road network, parks and green spaces was generated for CO and NO_2. To achieve this goal the geo referential data was analysed with QGIS software and python. Data layers were downloaded from Portal Lisboa Aberta. The road network was also categorized into its three hierarchical levels, as defined by the Lisbon Municipality Master Plan, (Fig. 2). A temporal analysis was also carried out, one of the results of this analysis is presented in Fig. 4, that shows how the CO levels behave hourly, on average. A similar approach was used to study the daily and monthly behaviour of CO levels. Furthermore, it was calculated how many times the pollution levels, in each sensor, crossed the limit specified by the authorities, the Lisbon Municipality (CML) and the World Health Organization (WHO). The limits are presented on table 2. According to the WHO, the exceedance of the air quality guideline levels is associated with significant risks to public health (WHO, 2021a).

Table 2. NO_2 and CO limit values (CML,2021), (WHO, 2021a).

Parameter	CML	WHO
CO	$CO < 10$ mg/m^3 (8-hour mean)	$CO < 4$ mg/m^3 (daily mean)
NO_2	$NO_2 < 200$ µg/m^3 (hourly) If $NO_2 > 400$ µg/m^3 (3 consecutive hours), then Alert	$NO_2 < 25$ µg/m^3 (daily mean)

4. Results

4.1. Infrastructure Map of the Lisbon Metropolitan Area

The Fig. 2 presents the infrastructure map of the Lisbon metropolitan area, showing the road and cycling network, green spaces, car parks, the location of underground, train, and boat stations. Only parks that have the capacity for more than 500 vehicles are included. The road network of Lisbon is presented and categorized in three hierarchical levels (level 1 – long distance routes, minimum 3 lanes, 70-90km/h, pedestrians and bicycles not allowed; level 2 – Inter-sectors distribution, minimum 2 lanes, 40-70km/h, pedestrians and bicycles allowed but segregated; level 3 – distribution within urban sectors and of proximity, minimum 1 lane, 30-50km/h, pedestrians and bicycles allowed but segregated). This data map, together with the following outputs, help finding the factors that influence CO and NO_2 emissions.

Fig. 2. Lisbon infrastructures and green areas.

4.2. Carbon Monoxide map representation

The Fig. 3 represents the mean CO values estimated for all the Lisbon metropolitan area, considering the measurements taken in the monitoring stations.

The location of roads network, the existence or absence of green spaces, and their size seem to condition the CO levels. There is no evidence that the road network hierarchy is a factor of pollution, but instead heavy traffic or road density might be. For example, by analysing the figure 3, it is possible to verify that in the old town and in the area around Saldanha and Avenida da República, which correspond to areas with very few green spaces, it is exactly where the highest average values of CO are registered. These areas have a very dense road network and heavy traffic.

For the period of analysis, the highest hourly mean value is obtained at Avenida da República station [A – Fig. 3] (0.6 mg/m^3), followed by Santa Apolónia [B – Fig. 3] on Avenida Infante Dom Henrique station (0.5 mg/m^3), Restauradores [C – Fig. 3] on Avenida da Liberdade (0.4 mg/m^3) and Largo de Madre Deus [D – Fig. 3] (0.4 mg/m^3). These high values occur along roads with high traffic. The absolute maximum CO value was obtained at the Santa Apolónia station, located at the waterfront closer to the old town, recording a value of 2.38 mg/m^3.

Most of these locations are well served by public transport, such as the metro and train, and bicycle lanes. The existence of collective transport and environmentally friendly means of transport do not necessarily exclude high levels of pollution, since they overlap with a dense road network. This means that users of public transport, bicycles and trolleys, as well as pedestrians, are exposed to the harmful pollution emitted by car users. Environmentally friendly mobility practices do not necessarily correspond to less exposure to pollution.

According to the Lisbon Municipality, the alert for CO is set when the average of the last 8 hours is greater than 10 mg/m^3. For the case study, this limit was not exceeded during the analysed period. The WHO defined the guideline value of 4 mg/m^3 (24-hour mean) to protect the public from the health effects of CO, this limit was also never crossed during the period under study. The Fig. 4 shows how the CO values behave during the day.

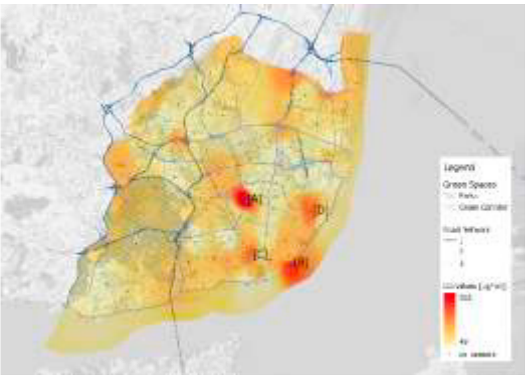

Fig. 3. Mean hourly CO values (between June 15th, 2021, and February 28th, 2022), and the respective monitoring stations.

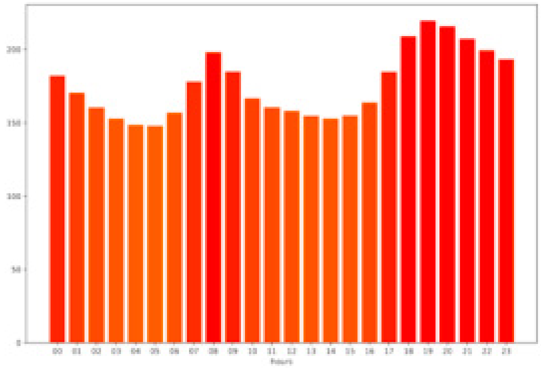

Fig. 4. Mean hourly CO values (between June 15th, 2021, and February 28th, 2022).

Two peaks can be easily identified. The first peak reaches its highest value at 8 a.m. and the second peak reaches its maximum at 7 p.m. These two peaks reflect the hours with highest volume of cars around the city due to the citizen's work schedule. It is also possible to identify a significant difference between both peaks, the first peak plays out much faster than the second.

4.3. Nitrogen Dioxide map representation

The Fig. 5 shows the mean NO_2 values predicted for the Lisbon metropolitan area, considering the measurements on the monitoring stations.

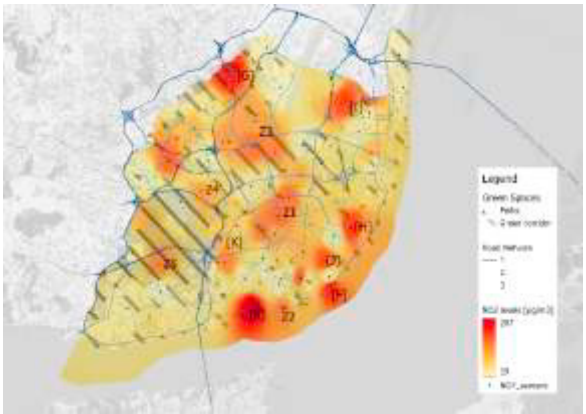

Fig. 5. Mean Hourly NO_2 value (between June 15th, 2021, and February 28th, 2022), and the respective monitoring stations.

As seen for the CO, also for the NO_2, the road network density and heavy traffic might have a stronger impact on the level of pollution than the road categorization. For NO_2 some high levels are also found in green areas. And again, environmentally friendly public transport and bicycle lanes are not necessarily located in areas with lower pollution, as is the example of Saldanha and its surroundings [Z1 – Fig. 5], and the waterfront closer to the old town [Z2 – Fig. 5], but also the corridor between Campo Grande and Odivelas [Z3 – Fig. 5], and the zone nearby Benfica and Carnide [Z4 – Fig. 5]. Also, some zones of the largest green area, Monsanto [Z5 – Fig. 5], show considerable levels of NO_2. In general terms, the areas of Parque das Nações and Belém seem to be the less affected by NO_2, exactly where there is a combination of less road density and the existence of some green areas.

The classification of the Lisbon's Municipality metadata defines four emission categories for the Lisbon Environmental Index (CML, 2021) of the NO_2. If the NO_2 values are between 0 and 100 μg/m³, the environmental index is green (normal level). If they are between 101 and 200 µg/m^3, it is yellow (moderate level). If the values are between 201 and 400 µg/m^3, it is orange (high level). If it is greater than 401 µg/m^3, it will be red (very high level). The maximum mean value calculated was obtained in the Avenida 24 de Julho [E – Fig. 5], and it is equal to 207 µg/m^3, which means that this location is frequently classified in the orange category.

Several monitoring stations have mean values that fall within the moderate level. It is possible to highlight Av. Infante D. Henrique, St. Apolónia [F – Fig. 5] (184 µg/m^3); Calçada de Carriche [G – Fig. 5] (176 µg/m^3), Largo Madre Deus, near Beato [H – Fig. 5] (162 µg/m^3); Alameda da Encarnação [I – Fig. 5] (156 µg/m^3); and Rua dos Sapadores [J – Fig. 5] (151 µg/m^3), since they have the highest mean NO_2 values.

As mentioned above, the number of times that the NO_2 values crossed the limit was calculated. According to CML in 2021, the alert on NO_2 is set when for 3 consecutive hours the values are greater than 400 µg/m^3. During the period under analysis, this alert was set 9 times on the sensor located in Rua de Campolide [K – Fig. 5].

On the other hand, the limit set by the WHO is regularly broken. The limit states that the average daily value of NO_2 must be lower than 25 µg/m^3. It was calculated, for each sensor, the percentage of days that the WHO's limit was surpassed. Table 3 presents this information.

Table 3. Number of sensors that set off the WHO NO_2 alert, by percentage of days.

Count	>90%	90-70%	70-50%	50-30%	30-10%	<10%
Absolute	46	13	0	3	3	0
Relative	70.8%	20%	0%	4.6%	4.6%	0%

As table 3 shows, 46 sensors, representing 70.8% of the NO_2 sensors, surpass the recommended values by the WHO on more than 90% of the days. Following, 20% of the sensors broke the limit in between 90 to 70% of the days. Only 6 of the sensors broke the limit on less than 50% of the days. There are no sensors that never break the limit in all Lisbon metropolitan area.

This information shows that the two alerts, the one set by CML, and the one set by WHO, are not balanced, the first is almost never set during all the period under analysis, while the second is broken regularly in most locations.

5. Conclusions and perspectives

To reduce the main sources of air pollution due to combustion gases, energy policies and investments that support the energy transition can be taken. In order to improve the air quality in the municipality of Lisbon, it is essential that the population choose to travel on foot or by bicycle on short journeys, favouring the use of public transport and choosing to share the car whenever possible. These solutions contribute to the reduction of traffic jams and, consequently, to the improvement of air quality, and, consequently, the population's exposure to these compounds.

Many examples of public policies applied to the transport sector promise to help achieve the decarbonization targets. An example of this is the shift from gasoline and diesel to lower carbon fuels or to electric vehicles, whether through batteries or fuel cells; the increase in cycling and pedestrian routes; and investment in the public transport network.

The Lisbon Municipality has been making efforts to improve air quality by implementing cycle paths, changes to the road network and an increase in green spaces. However, active users of environmental means of transport, that is who adopt environmentally friendly mobility practices, are passively exposed to high levels of pollution in some parts of Lisbon, such as Avenida da República, Avenida da Liberdade nearby Restauradores, Santa Apolónia in Avenida Infante Dom Henrique, and Avenida 24 de Julho, since a dense public transport network, metro and train, and bicycle lanes, overlap with a dense road network where there is higher pollution. Therefore, environmentally friendly mobility practices might not necessarily eliminate the harmful exposure to pollution. This way, the municipality of Lisbon shows a double pattern of environmental inequalities: a) inequality in the production of pollution, depending on the means of transport used, (private, public, and more or less environmentally friendly); and b) inequality in pollution exposure, which depends on location, public transport system, road network density and urban planning. At some locations, when these two inequalities overlap, a gap or a mismatch, between practices and exposure arises.

In the future, it is important to map overlapping patterns of mobility practices, and evaluate the exposure to pollution on a social scale. Understand how environmental inequalities relate to social indicators, that is, which social categories have friendly environmental practices and which do not. Specifically, it is relevant to determine who is an active polluter and actively exposed, who is an active polluter but little exposed, who is not a polluter and not exposed, and who is not a polluter but passively exposed. We also intend to analyse whether the temporal factor, i.e., the pollution monthly evolution, combined with the socio-cultural context, could allow to draw more conclusions.

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