Article

Using smart city tools to evaluate the effectiveness of a low emissions zone in Spain: Madrid Central

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Abstract: Population concentration in cities brings new risks as an increase in pollution, which causes urban health problems. In order to address this problem, traffic reduction measures are being implemented, as pedestrianization areas and the definition of Low Emissions Zones (LEZ). When the effectiveness of these types of measures is in doubt, smart city tools provide data that can be used to scientifically asses their impact. This article analyzes the situation of Madrid Central (Spain), a LEZ subject to controversy. We apply statistical and regression analyses to evaluate the effectiveness of this measure to reduce air pollution and outdoor noise. According to the results, this LEZ was able to significantly reduce NO_2, $PM_{2.5}$, and PM_{10} concentration locally, having the same positive impact in the rest of the city. In terms of noise, this measure is able to mitigate background noise levels generated by the road traffic.

Keywords: Air Pollution; Noise Pollution; Low Emissions Zone; Pedestrianization

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1. Introduction

Urbanization trends worldwide show a clear preference of the population to live in urban areas: today, 55% of the world's population lives in urban places and this proportion is expected to increase to 68% by 2050 [1]. The attraction of the city lies in the numerous opportunities resulting from the agglomeration of human capital and the associated economic dynamism. But, while it is true that urban areas are key for social change, wealth generation, and innovation, the concentration of people in cities also leads to new risks from an economic, social, and environmental point of view.

It is not uncommon for cities to be car-use oriented, with a design characterized by lack of safe public spaces that tend to discourage physical activity [2]. Nonetheless, major concern derived from the rapid development of car-oriented cities is the high generation of emissions (air pollutants and noise) and their impact on the inhabitants' health [3]. Another related problem is the increase of environmental noise, which originates a range of health problems including annoyance, sleep disturbance, increasing hypertension, and cardiovascular diseases [4]. In this regard, the speed of urbanization has outpaced the ability of governments to build essential infrastructures that make life in cities safe, rewarding, and healthy [5].

As about 80% of this pollution associated with health problems is produced by cars [6], reducing traffic seems to be an efficient strategy to improve urban livability and their inhabitants' health. Thus, many cities around the world started to shift toward non-car friendly access (pedestrianization measures) because is an effective and non-expensive way to reduce air pollution and noise [3,7–10].

According to the European Commission, a smart city goes beyond the use of information and communication technologies (ICT) for better resource use and less emissions [11]. In fact, different smart city tools and smart city management can be an invaluable tool in order to fulfill the government's commitment to the citizen. Taking advantage of this approach and, in order to measure effectiveness or even to scientifically guide the process, we can benefit from put into use air quality monitoring and other tools that smart city provides, e.g., internet of things (IoT) and open data.

In this work we analyze with smart city tools the effectiveness of the implementation of Madrid Central (MC), a Low Emissions Zone (LEZ) in Madrid, Spain. This approach is specifically needed here because of the controversy around MC and its use as a political symbol. Despite the fact that this LEZ was actually an extension and continuation of previous measures with the goal to comply with a European air quality requirement, MC encountered strong opposition. Those claiming for the supposed right to go by car accused this measure as non-effective over the reduction of pollutants and accusing it of cause border-effect (pollution displacement). Fulfilling its electoral promise, after the elections the new government decided to reverse MC measures.

This article is an extension of a preliminary study in which this pedestrianization measure was locally evaluated in terms of its impact on the LEZ on subset of pollutants [12]. The data used in that study comprises a time frame of 30 months (between December 2016 and May 2019), even if MC was active just during six months. According to the results obtained, the research concluded that MC was effective in reducing the concentration of NO_2 and noise in the area.

This new analysis considers a longer amount of time and a more comprehensive range of pollutants. This piece also takes into consideration a bigger area of the city in order to check potential side effects. Therefore, in this article, we face the following research questions: **RQ1:** *Is the deployment of MC effective to reduce the concentration of NO_2 and so improving the air quality in this area?* **RQ2:** *Is the definition of a LEZ an effective measure to reduce environmental noise levels?*. **RQ3:** *Do pedestrianization policies in a given area of the city produce a pollution displacement to other zones of the city?*. **RQ4:** *Are smart city tools effective for evaluating urban health policies and other measures implemented in the city?*.

The main contributions of this study are: *i)* evaluate the effectiveness of traffic limitation measures in reducing emissions harmful to health; *ii)* analyze the impact of such measures on environmental noise, which is also associated with poorer urban health; *iii)* check whether the accusation of pollution displacement (border-effect) has any basis according to results; and *iv)* appraise the usefulness of smart city tools as an appliance for evaluating urban measures and policies to reduce pollution.

The paper is organized as follows: first, the impact of pollutants on health is reviewed, MC is contextualized, and related research is introduced. Section 3.3 introduces the materials and methods used in this analysis. The evaluation of the impact of MC in terms of the air quality and noise is presented in Air quality and noise reduction is evaluated first locally (in the LEZ) and in the whole city in sections 4 and 5.2. Finally, Section 6 presents the conclusions and the main lines of future work.

2. Background

This section introduces first the main effects of car-use oriented cities on health. Next, it presents the EU directives on air pollution and the main aspects of the implementation of MC, including the municipal regulations on which it is based. Finally, it reviews relevant related work.

2.1. Designing cities for cars or for people? The effects on health and well-being

on safety and health, as well as over the general quality of life. An urban design focused on car use has had a negative effect on the quality of the social space in the city. This approach to the city forgets that the physical and spatial context has a deep influence on people throughout the whole course of life. It has been proved how the growth of car use reduces children's access to public space in urban contexts due to traffic and lack of infrastructure for pedestrians [13,14]. Restricting mobility is critical for the development of children's spatial awareness and spatial activity, affecting so their social and physical development [15]. Other groups, as the elderly, could benefit too from environments with safe walking access, improving their independence and well-being [16].

But traffic and car use causes a high generation of emissions, both air pollutants and noise. This leads to a range of urban health problems: reduces life expectancy, produces loss of years of a healthy life, and diminishes the quality of health [3]. Air pollution, which causes more than 400,000 premature deaths is considered the top health hazard in the European Union (EU) [17,18]. It has proved to be associated with heart disease and strokes, lung diseases, and lung cancer, besides reducing lung capacity and aggravating asthma. Air pollution has been also pointed out as carcinogenic and causes infertility and diabetes type 2 [19]. Other studies link air pollution to obesity, systemic inflammation, aging, Alzheimer's disease, and dementia [20]. It also affects the brain in the same way that Alzheimer's does as it causes changes in the structure of the brain [21]. While pollution affects all ages, some population groups are more vulnerable to pollution problems, as pregnant women, newborns, children, and the elderly. It also can exacerbate preexisting conditions at all ages.

Environmental noise is the major preventable cause of hearing loss [4]. It can also cause a range of non-auditory problems. To begin with, the evidence for the effects of environmental noise on health is strongest for annoyance, sleep disturbance, and cognitive performance in both adults and children [22]. Sound pollution also affects the cardiovascular system and causes hypertension [4,22]. Among children, it generates cognition problems as communication difficulties, impaired attention, increased arousal, frustration, and worst performance [23,24]. Last but not least, noise pollution causes annually at least 16,600 cases of premature death in Europe [25].

These risks could be reduced by limiting car use. Among different approaches to reduce car use, pedestrianization and LEZ have been proved as one of the most effective strategies against emissions. Absolute pedestrianization is difficult to be implemented (and expensive) but LEZ in different European Member States have proved to be successful. These are the cases for the LEZ ("Umweltzone") for trucks and cars in the center of Berlin inside the S-Bahn ring (Germany); the LEZ in the Lombardy Region for motorcycles, buses (whole year), and vehicles during wintertime, e.g. in Milan (Italy); or the LEZ for vans and lorries in Greater London (United Kingdom). All of these experiences have registered good results in terms of improving air quality.

2.2. Reducing pollution: international directives and the Low Emissions Zone in Madrid

While cities are related to social and economic progress, the increase of air pollution and noise can be considered a *modern plague* [26] decreasing the quality of life in cities [27]. In Europe (where 74% of the population lives in urban areas) the concern on this matter has led to the creation of a common set of environmental rules. These directives could not just safeguard EU citizens from environment-related pressures and risks to health and well being, but also reduce significantly different expenses: an adequate implementation of environmental legislation could save 50 billion euro every year in health and environment costs to the EU economy [20].

Because of this, a Clean Air Policy Package is adopted in 2013 by the the European Commission. This air quality policy, based on `Directive 2008/50/EC` [28] and `2004/107/EC` [29] rests on three pillars: *i)* air quality standards; *ii)* national emission reduction targets established in the National Emissions Ceiling Directive; and *iii)* emissions standards for key sources of pollution (as cars).

Being noise another harmful hazard, the EU regulation (`Directive 2002/49/EC`) [30] establishes for every Member State: *i)* the creation of noise mapping to determinate exposure levels to environmental noise; *ii)* made environmental noise information available to the citizen; *iii)* to adopt action plans, based upon noise-mapping results, to prevent and reduce environmental noise where necessary.

The referred Directive points road traffic are major noise sources, which has been also noted as the largest contributor to nitrogen oxide emissions [31]. For the reasons alluded previously, NO_2 is one of the main concerns of the EU: exposure to air pollution from road transport costs about 137 billion per year in Europe [32] but, more important, it produced around 76,000 premature deaths in 2015 [33]. Despite this, a number of countries keep exceeding the maximum established PM_{10} and the NO_2 levels. Spain is one of them, with several urban areas under surveillance by the EU because of their poor air quality. The European Commission required the reduction of these air pollutants under the threat of penalties.

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Madrid City Council decided to reduce transit traffic in a delimited area of the downtown replicating other European experiences. Madrid Central is a LEZ in Madrid, consisting of a number of car access restrictions for non-residents, independent from the current pollution level of the air.

The clarity in the perimeter of MC is one of their virtues, facilitating so the understanding of zonal delimitation and helping to introduce a behavioral change in the city.

MC is created by the *Ordenanza de Movilidad Sostenible* (October 5th, 2018) and it covers almost the entire *Centro* district, which is formed by the neighborhoods of *Palacio*, *Embajadores*, *Cortes*, *Justicia*, *Universidad*, and *Sol*. In this area, of 4,720,000 m^2, *Centro* inhabit 134,881 people, of which 21.6% are over 65 years old and 9.2% are less than 17 years old. Children and the the elderly are the age groups which can benefit more from the reduction of noise and pollutants.

The goal of MC is to improve air quality, but also respond to the idea of changing the uses of spaces in the city center, prioritizing the pedestrian one and reducing noise pollution. But as we said, its conformation mainly responds to ensure the objectives demanded by the EU. The traffic restriction started on November 30, 2018, and the fines for noncompliance did not start until March 16, 2019. Thanks to this straightforward measure, Spain avoided being brought to the European Court of Justice and so, the economic fine.

However, the measure raised strong opposition from some political parties. After the elections (held on May, 26th 2019) and qualifying the MC measures as inefficient and even unnecessary, the newly elected government approved art. 247 of the *Ordenanza de Movilidad Sostenible*, applying with it a moratorium on fines from July 1st to September 30th, 2019. Besides a warning from the EU, the decision raised social protests, especially from environmental groups. This suspension led to the emergence of social movements claiming the paralyzation of this reversal based on the negative effects over health and environment, and a warning from the EU. Finally, after a contentious-administrative appeal filed by the Platform in Defense of Central Madrid, a judge reactivated MC suspending the moratorium in fines.

2.3. Related works

The proliferation of pedestrianization measures and policies in different cities has led to a number of studies to evaluate their efficacy. A brief review of the related literature is presented next.

The impact of the rapid growth of car ownership in Beijing, China was analyzed in terms of transportation, energy efficiency, and environmental pollution [34,35] A set of measures were applied in Beijing in 2010 to mitigate the effects of traffic congestion and reduce air pollution. Liguang et al. [34] analyzed data from Beijing Municipal Committee of Transport to evaluate the implementation of car use restriction measures. Fairly good effects on improving urban transportation and air quality were achieved according to the results reported. Liu et al. [35] proposed an indirect approach to evaluate the impact of car restrictions and air quality, by applying a generalized additive model to explore the association of driving restrictions and daily hospital admissions for respiratory diseases. Several interest facts were obtained from the analysis, including higher daily hospital admissions for respiratory disease for some days, and the stronger effect on cold season. Female and people older than 65 years benefited more from the applied environmental policy. Overall, authors found positive effects on the improvement of public health. More research had been performed addressing the LEZ analysis in China [36–38].

In Europe, more than 200 LEZ were deployed during the last years [39]. Studies on their impact on urban air quality have been performed in several countries: Netherlands [40,41], Denmark [42], United Kingdom [43,44], Germany [45,46], Italy [47] and Portugal [48,49]. Most of them analyzed and acknowledge the reduction of two hazardous pollutants: nitrogen dioxide (NO_2) and particulate matter (PM).

Regarding noise pollution, there are is a body of work on analyzing urban noise and its impact on the population's health [50–55]. There is just a few research done on this regard [12,56]. However, most of the studies presented above studied also some variables related to noise pollution.

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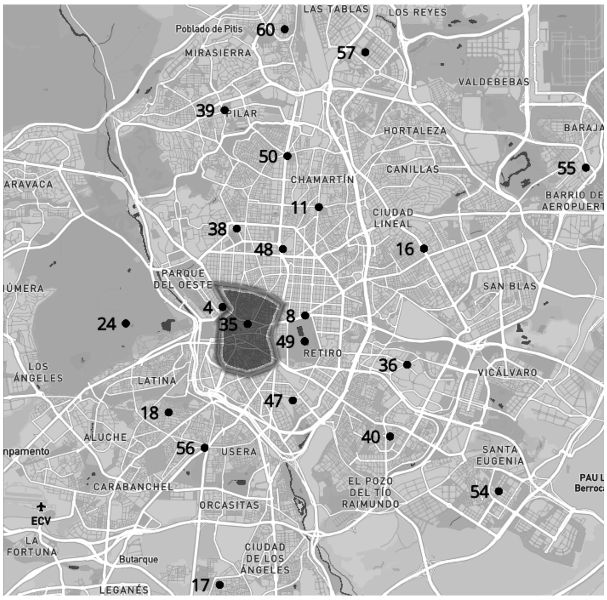
Focusing on Madrid, air quality has been been a health issue for the last decades. Thus, there are several studies dealing with air pollution in this city. Borge et al. [57] reported the modeling activities carried out in Madrid emphasizing the atmospheric emission inventory development which comprises the combination of models and real data. They showed that Madrid required to reduce NO_x emissions to meet the NO_2 European standards, which was the main motivation to implement MC. Different models were used to simulate and evaluate a short-term action plan to mitigate pollution emissions [58, 59]. More recently, after the application of MC, Lebrusán and Toutouh [12] evaluated the effectiveness of this measure in reducing pollution inside the LEZ. Another study, applied computational intelligence (deep neural networks and regression analysis) to evaluate the evolution of NO_2 concentration in the air, but again only locally (inside the MC area) [60]. Both reported a decrease in the NO_2 concentration. Our article contributes in this line of research by extending the set of pollutants studied by adding PM among others, taking into account a longer time frame, and including 24 areas of study in order to get a more general idea of the impact of this type of measures in whole Madrid.

3. Materials and methods

The primary goal of this study is to take advantage of smart city tools, such as a sensor network and open data, to evaluate the effects of a LEZ on environmental pollution and noise. We address such an analysis, first locally, evaluating the impact of this measure at the MC area, and globally, by assessing the same in different areas of the city (Madrid).

Madrid City Council installed different sensors (see Figure 1) that gather data on ambient concentration of different pollutants and measure the output noise levels. The data is available on the Open Data Portal Madrid City Council [1]. We use such open data in this research.



Sensor id.	Sensor location
4	Pza. de España
8	Escuelas Aguirre
11	Avda. Ramón y Cajal
16	Arturo Soria
17	Villaverde
18	Farolillo
24	Casa de Campo
35	Pza. del Carmen
36	Moratalaz
38	Cuatro Caminos
39	Barrio del Pilar
40	Vallecas
47	Mendez Alvaro
48	Castellana
49	Parque del Retiro
50	Plaza Castilla
54	Ensanche de Vallecas
55	Urb. Embajada
56	Pza. Elíptica
57	Sanchinarro
58	El Pardo
60	Tres Olivos

Figure 1. Location of the sensors that gathers the pollution information shared through the ODP. The shaded area represents the LEZ analyzed in this article.

The analysis is performed considering a temporal frame of six years (72 months), from December 2013 to November 2019. Two periods are distinguished: `Pre-MC`, i.e., the period of five years before implementing MC (from December 2013 to November 2018), and `Post-MC`, i.e., the period of one year after implementing the mobility measure (from December 2018 to November 2019). The main idea is to compare both periods to asses the effect of the measures applied in MC.

[1] Madrid Open Data Portal URL: `https://datos.madrid.es/`

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Following, we introduce the air pollutants analyzed, the outdoor noise metrics studied, and the methodology applied in the evaluation.

3.1. Air quality evaluation

The Open Data Portal (OPD) provides the hourly mean concentration of several air pollutants. In this study we focus on six: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), particulate matter 10 micrometers or less in diameter (PM_{10}), and particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$). Table 1 summarizes the maximum concentration allowed of the studied pollutants established by WHO and EU directives.

Table 1. Maximum concentration allowed of pollutants in the air by the WHO and EU regulations.

Pollutant	Averaging period	WHO theshold concentration	EU theshold concentration
SO_2	24 hours	20 $\mu g/m^3$	125 $\mu g/m^3$
	1 hour	-	350 $\mu g/m^3$
	10 minutes	500 $\mu g/m^3$	-
NO_2	1 year	40 $\mu g/m^3$	40 $\mu g/m^3$
	1 hour	200 $\mu g/m^3$	200 $\mu g/m^3$
O_3	8 hours	100 $\mu g/m^3$	120 $\mu g/m^3$
CO	8 hours	10 mg/m^3	10 mg/m^3
PM_{10}	24 hours	50 $\mu g/m^3$	50 $\mu g/m^3$
	1 year	20 $\mu g/m^3$	40 $\mu g/m^3$
$PM_{2.5}$	24 hours	25 $\mu g/m^3$	25 $\mu g/m^3$
	1 year	10 $\mu g/m^3$	-

3.2. Noise evaluation

It is not trivial to chose the right parameters to evaluate noise pollution and its impact on the people. The sound-meters return measures that describe the physical attributes of the sound, but not the subjective response and the physiological and psycho-social harm extent to the public. The noise pollution data provided by the OPD includes the daily mean of the equivalent sound pressure levels, the percentile noise levels [61], and the noise pollution level (NPL) [62]:

- **Equivalent sound pressure levels** (L_{eq}) can be described as the average sound level for the measurement. The data analyzed include the L_{eq24} that corresponds to the noise measured during the whole day (24 hours). In addition, three L_{eq} are returned by taking into account the period of the day: L_{eqD}, L_{eqE}, and L_{eqN}, which are evaluated during the day (from 7:00h to 19:00h), evening (from 19:00h to 23:00h), and night (from 23:00h to 7:00h), respectively.
- **Percentile noise levels** (L_x) are the levels exceeded for x percent of the time, where x is between 0.1% and 99.9%. L_x is calculated by applying statistical analysis. We evaluate the L_{10}, L_{50}, and L_{90}. The L_{10} and L_{90} are extensively used for rating any annoying traffic noise and background noise, respectively.
- **NPL** was developed to estimate the dissatisfaction caused by road traffic noise comprising the continuous noise level (L_{eq}) and the annoyance caused by fluctuations in that level. NPL is equal to L_{eq} plus 2.56 times the standard deviation of the noise distribution and it is generally approximated by Equation 1.

$$NPL \approx L_{eq} + (L_{10} - L_{90}) \tag{1}$$

All sound levels referred in this article are measured in terms of A-weighted decibel (dBA), which corresponds to the A-weighted sound level readings to replicate the response of the human ear to the annoyance caused by road traffic noise.

The Guideline Development Group (GDG) of WHO strongly recommends reducing L_{eq} noise levels produced by road traffic below 53 dBA. Road traffic noise above this level is associated with

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adverse health effects. Specifically, for night noise exposure (L_{eqN}), the GDG strongly recommends reducing noise levels produced by traffic flows below 45 dBA, since road traffic noise above this level is associated with adverse effects on sleep [63]. According to the Community of Madrid regulations presented in the *Normativa de ruido diurno y vibraciones* [64], the L_{eq} levels should be between 50 and 65 dBA during the day time and between 40 and 55 dBA during the night.

3.3. Methodology

In order to asses the effectiveness of the LEZ(see Section 2.2), we evaluate the air pollution and the noise in the LEZ and in different areas of the city. Thus, we asses the local effect on the LEZ area and whether if it is possible that a border effect is occurring as a result of potential traffic diversion. (i.e., check the existence or absence of the border-effect). The analysis performed in this article mainly considers:

- The pollutant concentration or level of noise itself during both periods `Pre-MC` and `Post-MC`which is measured and averaged for periods of one hour and one day.
- The average difference between the pollutant concentration or level of noise x during `Post-MC` ($x^m_{\texttt{Post-MC}}$) and `Pre-MC` ($x^m_{\texttt{Pre-MC}}$) taking into account different months (M). We denote this metric by Δ (see Eq. 2). Negative values of Δ denote reduction/improvement of x.
- The percentage of the time the population is exposed to air pollutant concentration or noise levels bellow to the thresholds defined by EU denoted by τ. This thresholds are shown in Table 1. The value of τ allows the assessment of the effectiveness of MC to potentially improve urban health, because there may be situations where the pollution or noise is reduced but the situation is still unhealthy according to the EU regulations (e.g., NO_2 concentration $> 40\ \mu g/m^3$).
- Polynomial regression is applied to evaluate the general trend in the air pollution concentration or levels of noise with and without the implementation of the road traffic restrictions in Madrid Central. Although is one of the simplest methods for analysis and estimation of time series, yet it is frequently used in the related literature [12,35,38] In this article, two polynomial regression methods are studied: linear and polynomial of grade 10.

$$\Delta = \frac{1}{|M|} \sum_{m \in M} x^m_{\texttt{Pre-MC}} - x^m_{\texttt{Pre-MC}} \qquad (2)$$

In order to determine the statistical significance of the results obtained, Shapiro-Wilks statistical test is applied to check the normality of the distributions and, as the results are not normally distributed, Mann–Whitney U rank test is used to asses if the pollutant is statistically reduced during `Post-MC`.

4. Pollution evaluation at the LEZ area

This section analyzes the information gathered by the sensor located in Pza. del Carmen (id. 35), which is the one inside of the LEZ. When evaluating the pollution in MC, we face two main drawbacks: first, the sensor does not gather information about $PM_{2.5}$ and PM_{10}, and second, the noise data shared through ODP does not provide complete data for 2013. Thus, we do not include in this section the analysis of these two air pollutants and `Pre-MC` period is defined from December 2014 to November 2018 when the noise is evaluated.

4.1. Air quality

Table 2 reports the minimum (Min), the maximum (Max), the median (Median), and the interquartile range (Iqr) for the concentration of the pollutants sensed in MC during the two periods analyzed here. The last column includes the value of Δ and the check-mark (✓) indicates that there is a statistical difference according to Mann–Whitney U test in such a pollutant for the periods analyzed (i.e., p-value$<$0.01). Table 3 presents the percentage of time τ that the air pollutant concentration is lower than the threshold defined by the EU.

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The evaluated measures are grouped by seasons because the meteorological conditions (i.e., wind direction and speed, atmospheric pressure, temperature, and relative humidity) affect the chemical behavior of the evaluated pollutants [65].

Figures 2, 3, 5, and 6 show the mean concentration of the pollutants by months. Notice that `Pre-MC`covers a wider amount of time. These figures also illustrate the boxplot of the concentration of the air pollutants for `Pre-MC` and `Post-MC` periods and the probability density function (PDF) of the whole data grouped by periods, i.e., `Pre-MC`and `Post-MC`.

Table 2. Summary of the air pollutants sensed. Negative values of Δ indicates a reduction of pollution and check-mark (✓) illustrates that there is statistical difference (p-value<0.01).

Season	Pre-MC				Post-MC				Δ
	Min	Median	Iqr	Max	Min	Median	Iqr	Max	
SO_2 concentration in $\mu g/m^3$									
spring	1.00	7.33	4.39	37.00	6.76	12.11	1.42	24.00	39.45
summer	1.00	8.90	5.94	50.00	1.00	10.49	1.98	17.00	15.19
autumn	1.00	8.33	5.53	53.00	1.00	11.69	6.38	35.00	28.70
winter	1.00	7.92	5.08	53.00	6.34	15.25	4.70	68.00	48.06
NO_2 concentration in $\mu g/m^3$									
spring	5.00	38.39	20.30	162.00	1.00	23.92	16.39	131.00	✓ -60.47
summer	3.00	39.79	22.74	196.00	8.00	34.33	19.46	139.00	✓ -15.88
autumn	1.00	56.37	26.31	224.00	5.00	41.68	23.93	123.00	✓ -35.25
winter	4.00	51.05	25.43	196.00	1.00	49.63	26.00	147.00	-2.86
O_3 concentration in $\mu g/m^3$									
spring	1.00	55.05	27.35	157.00	4.00	59.94	21.91	131.00	8.16
summer	1.00	63.40	32.83	215.00	1.00	52.74	26.45	135.00	✓ -20.20
autumn	1.00	26.49	22.80	134.00	1.00	31.77	21.26	112.00	16.61
winter	1.00	26.99	19.97	102.00	2.00	31.47	24.06	98.00	14.24
CO concentration in mg/m^3									
spring	0.10	0.31	0.13	1.90	0.10	0.54	0.24	3.00	43.06
summer	0.10	0.33	0.21	2.30	0.10	0.27	0.28	3.00	✓ -21.38
autumn	0.10	0.47	0.30	2.60	0.10	0.50	0.26	2.00	5.31
winter	0.10	0.45	0.27	2.90	0.10	0.45	0.34	4.10	✓ 0.17

Table 3. Percentage of time τ the air pollutant concentration is lower than the EU thresholds.

Period	SO_2	NO_2	O_3	CO
`Pre-MC`	95.81	46.88	97.96	100.00
`Post-MC`	94.48	62.17	99.63	100.00

The concentration of SO_2 in the air is higher during `Post-MC` than during `Pre-MC` for all the seasons (i.e., $\Delta > 0$). Figures 2 illustrates this increase. This is principally due to the largest sources of SO_2 emissions are from fossil fuel combustion at power plants and other industrial facilities [65]. Thus, mobility-related measures or policies are not appropriate for reducing the SO_2 concentration in the air.

For both periods, the mean concentration does not exceed the threshold defined by the EU (20 $\mu g/m^3$), however, the maxima values do (see Table 2). Table 3 shows that the population is under a SO_2 concentration lower than the UE threshold during 95.81% of the time for `Pre-MC` and 94.48% for `Post-MC`. Thus, the excess of this pollutant is exceptional and negligible, so it is not considered problematic in Spain.

Focusing on NO_2, which is the pollutant that almost lead Spain to the European Court and whose excess is a public health concern, its concentration is significantly reduced for all the seasons, but winter (i.e., Mann–Whitney U statistical test p-value<0.01). The decrease of NO_2 concentration is lower during winter because of the heavier use of combustion power plants for wintertime home heating (therefore, the road traffic may not be the main source of NO_2), as well as the fact that NO_2 stays in the air longer in the winter [65]. Figure 3.b confirms that warmer seasons have better air quality.

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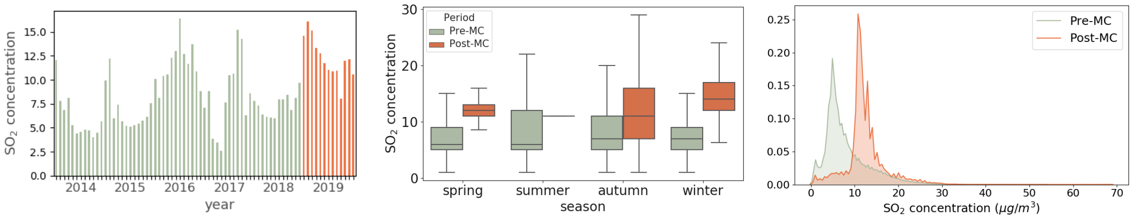
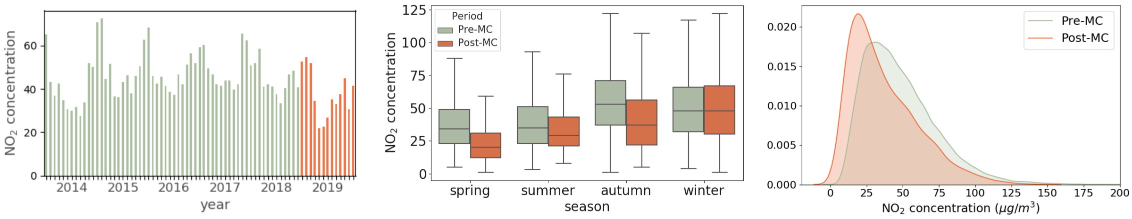


a) SO_2 mean concentration b) SO_2 boxplot c) SO_2 PDF

Figure 2. *Madrid Central* SO_2: a) monthly mean concentration, b) whole data concentration boxplot grouped by seasons, and c) whole data PDF.

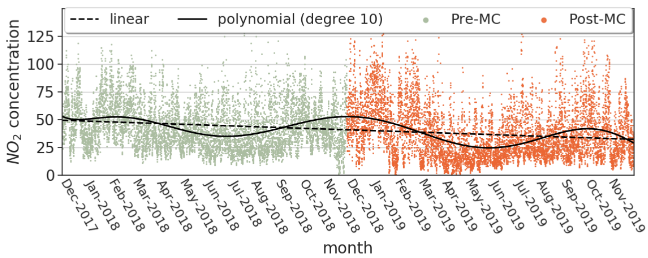


b1) NO_2 mean concentration. b2) NO_2 boxplot. c) NO_2 PDF

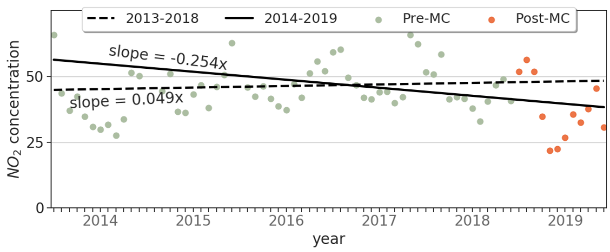
Figure 3. *Madrid Central* NO_2: a) monthly mean concentration, b) whole data concentration boxplot grouped by seasons, and c) whole data PDF.

As it can be seen in Figure 3.a, the concentration of NO_2 exceeds during several months the maximum one allowed by the EU for both periods (`Pre-MC` and `Post-MC`) but with important differences. Thus, Table 3 results indicates that after MC measures the population is under healthier air during 15.29% longer than during `Pre-MC`(62.17%-46.88%). Figure 3.c confirms that MC is under lower concentration of NO_2 in the air during `Post-MC`.

It is noticeable that there is a clear downward trend in the concentration of NO_2 after the application of the car restrictions (see Figure 3.a). We apply regression analysis to evaluate the general trend of this pollutant. Figure 4 illustrates two different experiments: first, we take into account all the hourly concentration values during the last two years to see the trend of the closest time (a), and second (b), the sensed values are averaged by months and there are evaluated the trends for the last five years previous to the MC measures (from 2014 to 2018) and for the last five years (from 2015 to 2019). This last experiment is to analyze the possible change of trend due to the new mobility policies.



a) Hourly values sensed during the last two years (from Dec 1st, 2017 to Nov 30th, 2019) grouped by hours.



b) Monthly values sensed during the last six years (from Dec 1st, 2013 to Nov 30th, 2019) grouped by months.

Figure 4. NO_2 values sensed at MC and the regression fitting.

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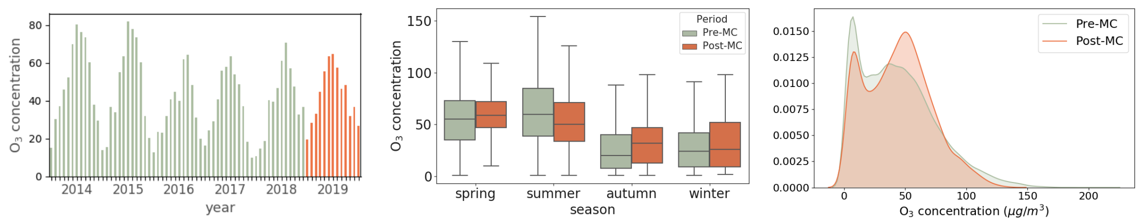
In Figure 4.a, the polynomial regression of grade 10 (black line) shows, first, how the NO_2 concentration increases during colder seasons and decreases in warmer ones and, second, that the pollution values during `Post-MC` are lower than `Pre-MC`. In turn, the linear regression (black dashed line) displays a declined trend over time for this air pollutant. In Figure 4.b, the black dashed line that represents the linear regression of the NO_2 concentration before applying MC (five years) has a positive slope (i.e., the NO_2 concentration tends to increase). The solid black line that represents the general trend after applying MC measures has a negative slope, which indicates that NO_2 concentration in the air tends to be reduced. Thus, the behavior of the concentration of NO_2 in the air under the application of MC measures points out that the traffic restriction has a positive effect on air quality.

The concentration of O_3 shows a similar behavior for both periods (see Figure 5 and Table 3). The results in Table 2 shows that the concentration of this pollutant has increased after the application of MC during spring, autumn, and winter, but it has decreased during summer. All the monthly averages O_3 values are lower than the maximum defined by the EU (120 $\mu g/m^3$). According to Table 3 values, the population is almost all the time under air without an excess of O_3 during `Post-MC`.

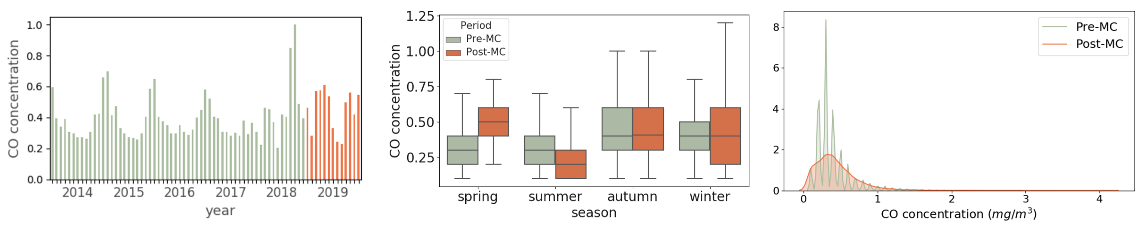


a) O_3 mean concentration b) O_3 boxplot c) O_3 PDF

Figure 5. *Madrid Central* O_3: mean concentration grouped by months (left side) and whole data concentration boxplot grouped by seasons (right side).

The increment of O_3, that we illustrate in our analysis, can be due by the oxidation of NO, i.e., the chemical reaction of O_3 and NO that forms NO_2 and O_2, which occurs in urban areas [66]. As the road traffic limitation reduces the concentration NO, the portion of O_3 that reacts with NO is lower. Therefore, the levels of O_3 do not decrease, and subsequently, the concentration of NO_2 produced by the oxidation of NO is lower. In short, this upturn can be a chemical consequence of the reduction in the air of other components concentration.

Regarding CO, as it occurs with O_3, the concentration of this pollutant decrease during summer, but increase during the other seasons (see Table 2 and Figure 6). Although one of the major sources of this pollutant to outdoor air is road traffic vehicles or machinery that burn fossil fuels, it seems that the reduction of road traffic does not lead to a decrease of CO in this case. However, according to the EU regulations, there is not a need of reducing CO since during the time frame analyzed in this article there is not any measurement over the threshold stipulated by the EU (10 mg/m^3).



a) CO mean concentration b) CO boxplot b) CO PDF

Figure 6. *Madrid Central* CO data: mean concentration grouped by months (left side) and whole data concentration boxplot grouped by seasons (right side).

Finally, the evaluation of the SO_2, NO_2, O_3, and CO indicates that the final environmental balance may not always coincide with what was intuitively expected. However, it is important to remark that MC measures are highly effective in reducing the NO_2 concentration which was one of the major motivations for making this move. Therefore the answer to **RQ1:** *Is the deployment of MC effective to reduce the concentration of NO_2 and so improving the air quality in this area?* is yes. The restriction to the road traffic applied in MC has significantly reduced the NO_2 concentration.

4.2. Outdoor noise in MC area

Table 4 reports the minimum (Min), the maximum (Max), the median (Median), and the interquartile range (Iqr) of the levels of noise sensed in MC during the two periods analyzed here. The last column includes the value of Δ and the check-mark (✓) indicates that there is a statistical reduction in such a noise level between `Pre-MC` and `Post-MC` according to Mann–Whitney U test(i.e., p-value<0.01). Table 5 presents the percentage of time τ that the outdoor noise levels are lower than the threshold values defined by Madrid City Council [64] (see Section 3.2). Figures 7, 9, and 10 show the mean of the noise levels noise evaluated here grouped by months.

Table 4. Summary of the levels of noise (in dBA). Negative values of Δ indicate a reduction of pollution and check-mark (✓) illustrates that there is statistical difference between the periods analyzed (p-value<0.01).

Season	Pre-MC				Post-MC				Δ
	Min	Median	Iqr	Max	Min	Median	Iqr	Max	
L_{eq24}	59.30	67.50	1.70	95.80	62.30	66.70	1.62	77.30	✓ -0.34
L_{eqD}	58.80	68.20	2.20	84.00	60.70	67.50	2.22	80.10	✓ -0.22
L_{eqE}	57.10	67.80	1.67	82.00	57.80	67.20	1.50	82.60	✓ -0.46
L_{eqN}	55.10	64.90	2.50	80.70	58.50	64.40	2.33	78.40	✓ -0.55
L_{10}	62.70	70.70	1.70	81.50	66.40	70.00	1.60	86.70	✓ -0.37
L_{50}	55.00	65.30	2.00	71.60	57.50	64.40	2.10	71.50	✓ -0.71
L_{90}	47.30	56.90	2.50	66.30	49.80	56.20	2.50	63.40	✓ -0.77
NPL	68.70	80.90	3.00	108.40	74.90	80.10	2.80	100.50	✓ -0.00

Table 5. Percentage of time τ the levels of noise are lower than the EU thresholds.

Period	L_{eqE}	L_{eqD}	L_{eqN}
`Pre-MC`	4.94 (3.04)	8.30 (3.47)	0.00 (9.93)
`Post-MC`	3.02 (2.39)	9.89 (3.22)	0.00 (9.38)

Regarding the equivalent sound pressure levels (L_{eq24}, L_{eqD}, L_{eqE}, and L_{eqN}), the level the noise is higher during the hours between 7:00h and 23:00h than during the night time (see Table 4 and Figure 8). This is mainly due to MC neighborhood is located in a commercial area and the business hours in Madrid usually end at 22:00h, thus there is road traffic until that late hours. There is a reduction in the median of all these noise levels during `Post-MC`. Therefore, in general, the noise is lower during this period. The highest differences between the two evaluated periods are given by the evening (L_{eqE}) and at night (L_{eqN}) noise levels (see Table 4).

Focusing on `Post-MC` time, the levels of noise decrease during the first months but they experience an increase after June, i.e., when MC suffered from the reversal (see Figure 7). If we focus on L_{eq24} and L_{eqD}, this increment is important. Taking into account the noise levels before the reversal, the reduction Δ for these two levels of noise is significantly higher, i.e., $\Delta(L_{eq24})$=-0.52 dBA and $\Delta(L_{eqD})$=-0.45 dBA. Thus, we can observe a negative impact on the noise pollution of the reversal, that is mainly suffered at the time between 7:00h and 19:00h.

Evaluating τ during `Pre-MC` and `Post-MC`, Table 5 shows that the outdoor levels of noise practically always surpass the thresholds of the city council. During the nights the levels of noise never are lower than 55 dBA, which is the threshold for these hours. Notice that we are evaluating equivalent sound pressure levels averaged for every day. Figure 7 also illustrates how the noise levels generally exceed the thresholds, i.e., the monthly average levels of noise are higher than 65 dBA for L_{eqD} and L_{eqE} and higher than 55 dBA for L_{eqN}. Therefore, other measures must be applied to further reduce outdoor noise in this area.

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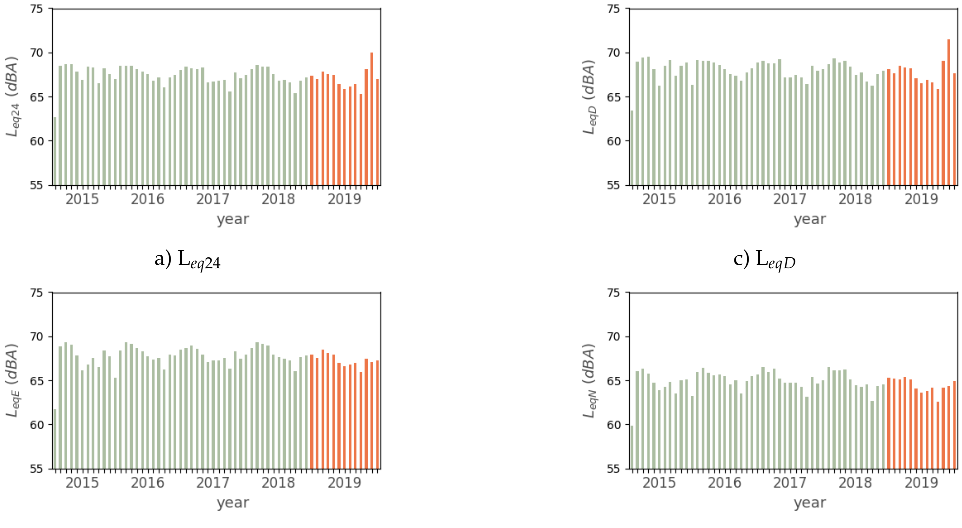
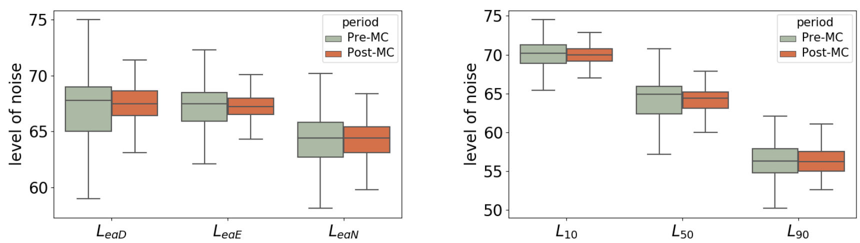


a) L_{eq24} c) L_{eqD} b) L_{eqE} d) L_{eqN}

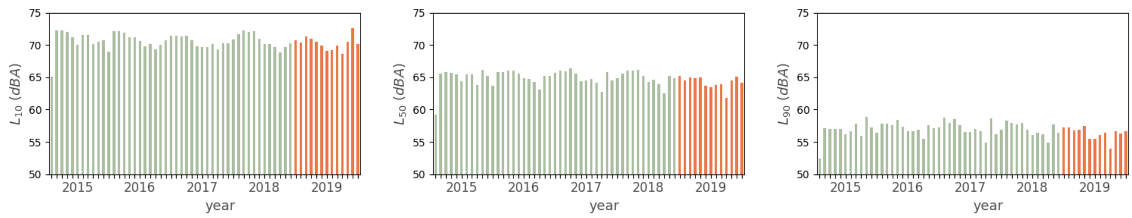
Figure 7. Mean levels of noise grouped by months.



a) Equivalent sound pressure levels boxplot b) Percentile noise levels boxplot

Figure 8. Boxplots of the levels of noise evaluated groped in `Pre-MC` and .

Focusing on the percentile noise levels (L_{10}, L_{50}, and L_{90}), `Pre-MC` and `Post-MC` differences are statistically significant. The best improvement Δ is shown by L_{90} (see Figure 4), which represents the residual background levels of noise of the urban area analyzed. As the continuous road traffic flow is one of the main sources of the background noise, the reduction of traffic transit provokes a decrease in this type of noise.



a) L_{10} c) L_{50} b) L_{90}

Figure 9. Mean percentile levels of noise grouped by months.

Regarding L_{50}, which statistically represents the median of the fluctuating levels of noise, is also reduced, i.e., $\Delta(L_{50})$=-0.71. The reduction of the annoying peaks in noise (i.e. L_{10}) is lower than for the other two percentile levels ($\Delta(L_{10})$=-0.37). This represents a limited decrease of 0.5% regarding the median value of this noise during `Pre-MC` (70.70 dBA).

There is not a statistically significant reduction of NPL (see Table 4) and the average improvement is 0.00. Besides, as the computation of this metric depends on L_{eq24}, it suffers from the same increase during the last months of `Post-MC` after the reversal of MC (see Figure 10).

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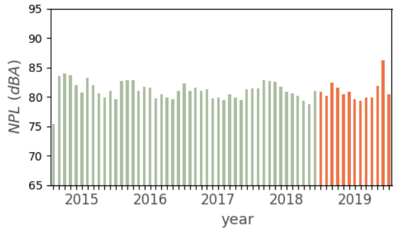
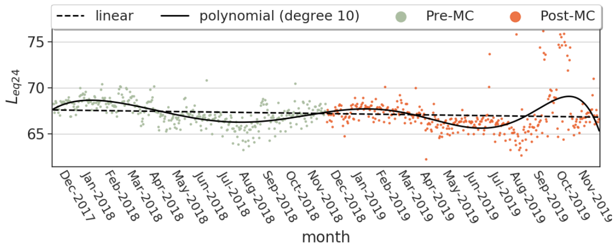
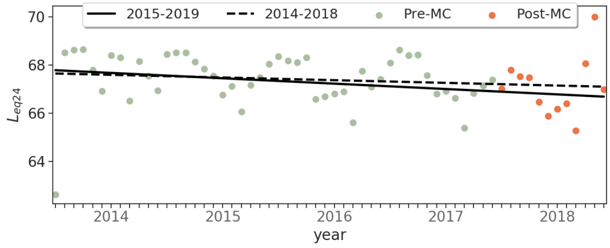


Figure 10. *Madrid Central* NPL monthly levels of noise.

Figures 11, 12, and 13 illustrate the trend of some representative levels of sound (L_{eq24}, L_{eqD}, and L_{90}). When evaluating the trend of the last two years (on top of each figure), we observe a similar behavior: *a)* the polynomial regression of grade 10 (black line) illustrates the most marked reduction of the levels of noise during `Post-MC` until June 2019 when the MC was reversed, and *b)* the linear regression (black dashed line) shows that the noise in MC is being marginally reduced over the time (i.e., the function presents negative slopes but close to zero).



a) Values sensed during the last two years (from Dec 1st, 2017 to Nov 30th, 2019) grouped by hours.



b) Values sensed during the last five years (from Dec 1st, 2014 to Nov 30th, 2019) grouped by months.

Figure 11. *Madrid Central* sensor data. L_{eq24} values sensed and regression fitting.

In the bottom of Figures 11, 12, and 13, the black dashed line that represents the linear regression of the levels of noise before applying MC (from 2014 to 2018) have slopes close to zero or even positive in the case of L_{eqD}, i.e., there is an increase of outdoor noise in the area. The solid black line that represents the general trend after applying MC measures (last four years) has a steeper negative slope, which is higher in the case of L_{90}. Thus, the car restrictions tend to improve the background noise generated by road traffic.

Finally, we have computed the PDF of the L_{eq24}, L_{eqD}, and L_{90} noise values to confirm that there is a slight reduction in the outdoor levels of noise in the area of MC. Figure 14 illustrates that the distributions of `Post-MC` sensed values are more likely to be lower than the `Pre-MC` ones (the `Post-MC` distribution is lightly shifted to the left). However, although there is such a reduction, it is notorious that other types of measures are needed to mitigate this source of health problems and discomfort because the levels of noise exceed the thresholds set by the institutions nearly all the time during both evaluated periods, `Pre-MC` and `Post-MC`.

According to these results, we answer **RQ2:** *Is the definition of a LEZ an effective measure to reduce environmental noise levels?*. MC slightly reduces the outdoor levels of noise, mainly the background noise produced by road traffic. However, this decrease is not enough to keep the noise in the range of healthy levels.

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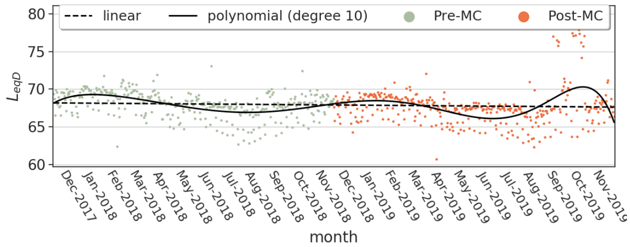
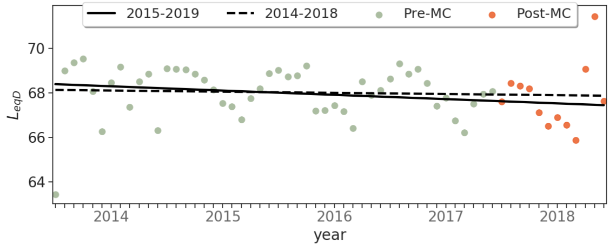
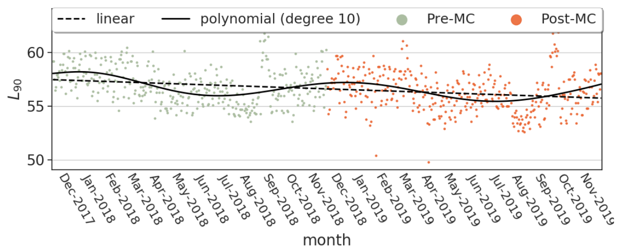


a) Values sensed during the last two years (from Dec 1st, 2017 to Nov 30th, 2019) grouped by hours.

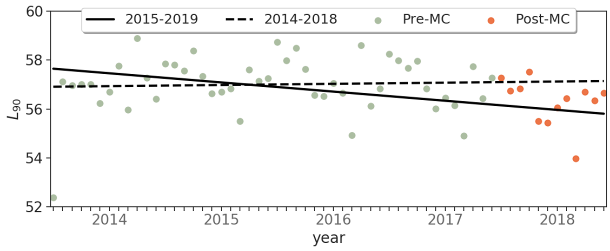


b) Values sensed during the last five years (from Dec 1st, 2014 to Nov 30th, 2019) grouped by months.

Figure 12. *Madrid Central* sensor data. L_{eqD} values sensed and regression fitting.



a) Values sensed during the last two years (from Dec 1st, 2017 to Nov 30th, 2019) grouped by hours.



b) Values sensed during the last five years (from Dec 1st, 2014 to Nov 30th, 2019) grouped by months.

Figure 13. *Madrid Central* sensor data. L_{90} values sensed and regression fitting.

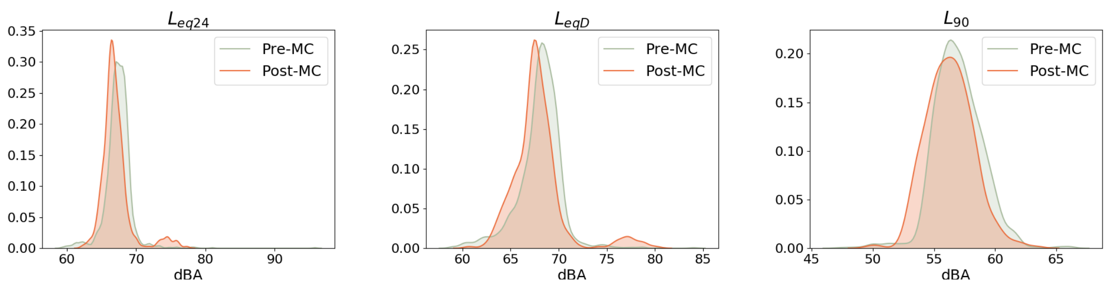


Figure 14. *Madrid Central* noise. PDF of the L_{eq24}, L_{eqD}, and L_{90} noise levels.

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5. Indirect repercussion on the pollution of the whole city

According to WHO and EU, NO_2 and particulate matter (PM$_2$.5 and PM$_1$0) are the main culprits in public health problems due to pollution. This section aims at taking advantage of the sensors network installed in Madrid to:

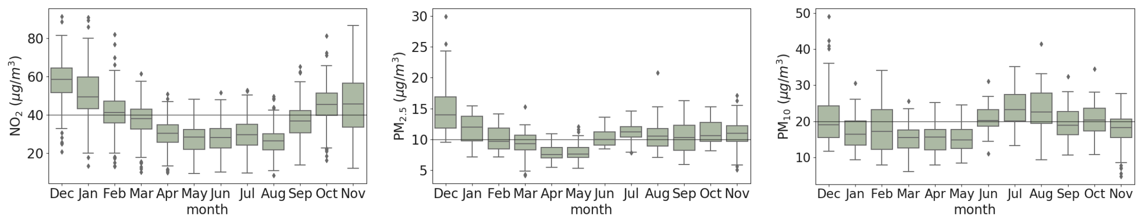
- first, confirm that the important reduction of NO2 emissions at MC area does not lead to an increase of such a pollutant in other zones due to a hypothetical redirection of traffic to other areas of the city, i.e., investigate the possible *border-effect* of MC, and
- second, analyze the concentration of the particulate matter in the areas where the sensors gather such an information in order to asses the possible impact on this aspect of the city due to MC measures.

The data provided by the ODP is incomplete and contains errors for several of the areas covered by the sensors. Only the data coming from sensors that correctly registered values for the whole time frame analyzed here are used in this analysis. Therefore, this section discusses data about NO_2 from 23 sensors, $PM_{2.5}$ from six, and PM_{10} from 12. This limits the areas of Madrid analyzed in our article. But it ensures that the data reflect reliably the concentration in the air of the pollutants analyzed.

5.1. Temporal variation in the air pollutants

In order to better understand the impact of NO_2, PM$_2$.5, and PM$_1$0 in Madrid, we evaluate their monthly trends that are shown in Figure 15. As seen in Section 4.1, NO_2 exhibits seasonal variations, with the highest concentrations in winter and the lowest in summer. During warmer months (from March to September) the median NO_2 concentration is lower than the EU threshold (40 $\mu g/m^3$). The highest NO_2 concentration is suffered during December and the lowest one during August.

This seasonal variation is mainly due to two different factors: the meteorological conditions and the emissions patterns. For example, temperature inversions and lower boundary layer heights in winter can avoid NO_2 to be ventilated from the boundary layer, leading to higher concentrations in European cities. In contrast, the increase of photochemical activity, solar radiation, etc. during summer lower NO_2 concentration [67]. In addition, fossil fuel combustion sources such as residential coal and and biomass combustion for heating also contributed to the formation of a high NO_2 concentration in wintertime.



a) NO_2 b) $PM_{2.5}$ c) PM_{10}

Figure 15. Monthly variations on NO_2, $PM_{2.5}$, and PM_{10}. The black horizontal lines represent the limits specified by the EU.

Focusing on $PM_{2.5}$, the highest concentration of this pollutant occurs in December (as it happens with NO_2). This pollutant presents a decreasing trend from December to May, being springtime the least polluted season. March, April, and May median values are the only ones that are lower than the threshold marked by the EU. For the months between June to November, the $PM_{2.5}$ concentrations tend to be slightly higher than the EU threshold and similar to each other. PM_{10} shows a similar seasonal variation than $PM_{2.5}$, from December to May there is a decrease in the concentration of this pollutant. July is the month with the highest PM_{10} concentration and May the month with the lowest one. In the case of this pollutant, June, July, August, and October median values surpass the EU threshold (40 $\mu g/m^3$).

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5.2. Effect of mobility restrictions on the NO_2 concentration at other areas of the city

The application of restrictions to vehicles to access a street or area affects the mobility patterns of the inhabitants in the whole city [3], and therefore, it impacts on the pollution in different areas of the same city. One of the main motivations of the deployment of MC was the reduction of this pollutant (see Section 2.2). In order to asses the effect of MC on the rest of the city of Madrid, we study the NO_2 concentration measured by sensors located through Madrid that gather the ODP data (see Figure 1). Thus, we evaluate the concentration of this pollutant during `Pre-MC` and `Post-MC`. Thus, we compute the difference between these two periods for each one of the sensed areas.

Table 6 shows the median (Med) and interquartile range (Iqr) of the daily sensed NO_2 concentration for each sensor grouped by years (these values are selected because the distributions are not normally distributed). The last column presents the Δ values. The minimum median concentration for each sensor is marked in bold. Finally, Figure 16.a illustrates the boxplots of the concentration for all the sensors for each year.

Table 6. Median NO_2 concentration and Δ values for the sensors analyzed.

Sensor location	Years												Δ
	2014		2015		2016		2017		2018		2019		
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	
Pza. del Carmen	34.0	34.0	44.0	37.0	44.0	31.0	44.0	32.0	41.0	28.0	**31.0**	32.0	✓ -8.87
Pza. de España	**34.0**	31.0	44.7	34.0	41.0	37.0	43.0	39.0	38.0	34.0	35.0	35.0	✓ -5.48
Avd. Ramón y C.	31.0	38.0	38.0	39.0	38.5	37.0	36.0	38.6	35.0	38.0	**33.0**	37.0	✓ -2.50
Arturo Soria	29.0	33.0	33.0	40.0	32.0	34.0	32.0	38.0	28.0	33.0	**27.0**	33.2	✓ -3.51
Villaverde	**27.0**	36.0	31.0	46.0	33.0	41.0	35.0	49.0	**27.0**	38.0	**27.0**	44.0	✓ -2.12
Farolillo	26.0	32.0	31.0	39.0	32.0	39.0	32.0	40.0	26.0	33.0	**25.0**	35.0	✓ -3.86
Casa de Campo	**12.0**	24.0	15.0	28.0	15.0	26.0	16.3	28.0	**12.0**	24.0	**12.0**	26.0	✓ -0.94
Barajas Pueblo	**25.0**	33.0	26.0	36.0	31.0	39.0	31.0	42.0	29.0	36.0	28.0	38.0	1.04
Moratalaz	**28.0**	30.0	33.0	36.0	34.0	33.0	33.0	36.0	30.5	34.0	29.0	36.0	✓ -1.48
Cuatro Caminos	35.0	35.0	36.0	41.0	35.0	37.0	37.0	40.0	34.0	37.0	**31.0**	38.0	✓ -3.13
Barrio del Pilar	31.0	36.0	32.0	40.1	33.0	35.0	32.0	39.0	30.0	35.0	**26.5**	38.0	✓ -3.79
Vallecas	33.0	35.0	29.0	37.0	32.0	38.0	32.0	39.0	28.0	33.0	**28.0**	36.0	✓ -2.93
Mendez Alvaro	**24.0**	35.0	29.0	41.0	30.0	41.0	33.0	45.0	26.0	36.0	26.0	37.0	✓ -2.89
Castellana	34.0	34.0	33.0	36.0	35.0	34.0	32.0	37.0	32.0	35.0	**28.0**	36.0	✓ -3.30
Par. del Retiro	19.0	22.0	25.0	31.0	26.0	33.0	23.2	35.0	22.0	27.0	**18.0**	29.0	✓ -4.34
Plaza Castilla	39.0	38.0	40.0	43.0	40.0	36.0	34.0	36.0	33.0	36.0	**31.0**	35.0	✓ -4.76
Ens. de Vallecas	**21.0**	28.0	31.0	43.0	27.0	40.0	28.0	40.0	27.0	33.0	27.0	37.0	0.75
Urb. Embajada	**31.0**	39.0	37.0	44.0	37.0	40.2	39.0	47.0	33.0	41.0	**31.0**	43.0	✓ -2.89
Pza. Elíptica	**46.0**	42.0	49.0	41.0	49.0	41.0	48.0	45.0	46.0	42.0	47.0	42.0	✓ -0.97
Sanchinarro	24.0	28.0	24.0	33.0	27.0	30.0	23.0	32.0	**21.0**	29.0	23.0	30.0	✓ -0.86
El Pardo	**9.0**	15.0	13.0	18.0	14.0	17.0	13.0	19.0	10.0	16.0	12.0	16.0	-0.02
Juan Carlos I	**14.0**	22.0	16.0	26.0	16.0	23.0	18.0	28.0	17.0	26.0	18.0	28.0	3.74
Tres Olivos	21.0	29.0	27.0	38.0	27.0	36.0	25.0	37.0	20.0	29.0	**18.0**	22.0	✓ -8.45

According to the results in Table 6, the median NO_2 concentration in the air during the year 2019 (i.e., `Post-MC` period) is the minimum for 14 of the 23 areas sensed. It is noticeable that 2014 is the year that has been sensed the minimum median concentration of this pollutant (for 11 of the 23 sensors). Thus, the years with lowest NO_2 concentration are fist 2019 and second 2014 (see Figure 16.a).

During the period from 2015 to 2018, several areas suffer from median NO_2 concentrations higher than 40 $\mu g/m^3$ (the EU threshold), which motivates the EU action to fine Spain and the following measures to define MC to avoid it. In 2019 and 2014 there are only the Pza. Elíptica sensor exceed this threshold. The main problem in this area is that it suffers from heavy traffic and congestion because its main road, the A-41 highway, connects Madrid with the southern towns.

As shown in the last column of Table 6, the highest reduction of the NO_2 concentration is sensed in Pza. del Carmen, which is in MC area. As expected, another important reduction is given at the area sensed by sensor installed in Pza. España (sensor id 4), which is the closest sensor to the MC area.

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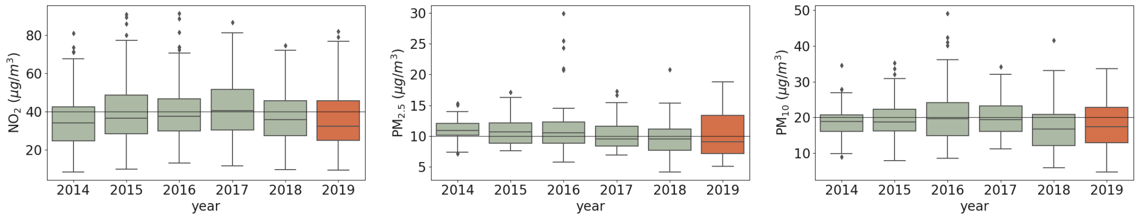


a) NO_2. b) $PM_{2.5}$ c) PM_{10}

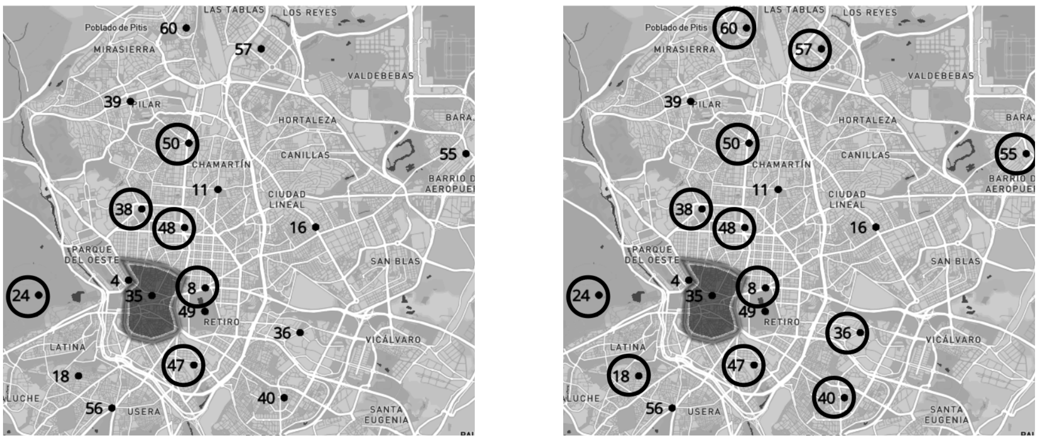
Figure 16. The city-wide daily concentrations of the evaluated pollutants during the study period grouped by years. The black horizontal lines represent the limits specified by the EU.

It experiences a reduction in the NO_2 concentration of 5.48 $\mu g/m^3$. In addition, there is a reduction in the average NO_2 concentration for all the sensed areas but three exceptions (Barajas Pueblo, Ens. de Vallecas, and Juan Carlos I, which are suburb areas far from the center of Madrid).

The results in Table 6 and Figure 16.a indicate that, in general, the deployment of the LEZ has a positive impact on the whole city because after that the air in Madrid generally is healthier (contains lower NO_2). This results are in line with the study that acknowledged that NO_2 concentration levels in Madrid are dominated by local traffic (up to 90%) [57]. Thus, reducing the road traffic leads to reduce NO_2 concentration in this city.

5.3. Repercussion on the particulate matter concentration in other areas of Madrid

As the sensor located at MC does not gather particulate matter concentration data, we analyze the effect of MC on this type of pollutants in different areas of the city. The number of sensors that gather trustworthy data during the time frame of our study is only six for $PM_{2.5}$ and 12 for PM_{10}. Figure 17 shows the location of these sensors. This limits the outcomes of this section about the concentration of these pollutants in the whole city.



a) Sensors that gather $PM_{2.5}$ data a) Sensors that gather PM_{10} data

Figure 17. Location of the sensors that gather particulate matter concentration data.

Tables 7 and 8 present the median (Med) and interquartile range (Iqr) of the daily sensed concentration of $PM_{2.5}$ and PM_{10}, respectively, for each sensor grouped by years. The last column presents the Δ values (difference between `Pre-MC` and `Post-MC`). The minimum median concentration for each sensor is marked in bold. Finally, Figures 16.b and 16.c show the boxplots of the concentration for all the sensors for each year of $PM_{2.5}$ and PM_{10}, respectively.

There are only six sensors able to provide trustfully data about $PM_{2.5}$ during the time frame of our study and they are located in the downtown of the city (see Figure 17.a). Five of these six sensed areas show the minimum concentration of of this pollutant during 2019 (see Table 7). The sensor that does not presents its minimum during 2019 (Casa de Campo sensor id 24) is located in the center of a large

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Table 7. Median $PM_{2.5}$ concentration and Δ values for the sensors analyzed.

Sensor location	2014		2015		2016		2017		2018		2019		Δ
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	
Casa de Campo	**7.0**	6.0	8.0	9.0	8.0	9.0	9.0	9.0	6.0	8.0	8.0	8.0	-0.06
Cuatro Caminos	10.0	11.0	9.6	8.0	9.0	9.0	9.0	8.0	**8.0**	8.0	**8.0**	8.0	✓ -0.49
Mendez Alvaro	**9.0**	8.0	**9.0**	9.0	**9.0**	11.0	10.0	10.0	**9.0**	10.0	**9.0**	9.0	✓ -0.68
Castellana	**8.0**	9.0	9.0	4.0	9.0	9.0	8.0	7.0	8.0	8.0	**8.0**	8.0	✓ -0.05
Plaza Castilla	10.0	7.0	9.0	8.0	9.0	9.0	8.0	7.0	8.0	8.0	**7.0**	8.0	✓ -0.75
Escuelas Aguirre	10.0	7.6	11.0	9.0	10.0	10.0	10.0	8.6	**9.0**	9.0	**9.0**	10.0	✓ -0.80

(Years span 2014–2019.)

park (green area). In addition, Casa de Campo presents the lowest $PM_{2.5}$ concentration in comparison with the others. Among the analyzed years, the median of the $PM_{2.5}$ concentration during 2019 is the lowest one (see Figure 16.b). For all the evaluated areas, there is a decrease on the concentration of this pollutant, which is statistically significant for five of them. This is expected because the main source of $PM_{2.5}$ in Madrid is the road traffic according to the *Screening for High Emission Reduction Potentials for Air quality* tool (SHERPA) developed by the Joint Research Centre to quantify the origins of air pollution in cities and regions [68].

Table 8. Median PM_{10} concentration and Δ values for the sensors analyzed.

Sensor location	2014		2015		2016		2017		2018		2019		Δ
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	
Farolillo	15.0	15.0	18.0	16.0	15.0	16.0	22.0	20.0	14.0	17.0	**13.9**	13.0	✓ -4.12
Casa de Campo	13.0	12.0	15.5	14.0	14.0	16.0	17.0	16.0	12.0	14.1	**11.0**	12.0	✓ -4.19
Moratalaz	**17.0**	21.0	18.0	21.0	**17.0**	20.0	20.0	17.0	18.0	17.0	**17.0**	16.7	-1.00
Cuatro Caminos	**14.0**	12.0	16.0	13.0	16.0	17.0	16.0	15.0	**14.0**	16.7	17.0	16.0	1.10
Vallecas	14.0	14.0	15.0	18.0	13.0	17.0	15.0	19.0	14.0	17.0	**13.0**	16.0	✓ -1.82
Mendez Alvaro	15.0	14.0	16.0	15.0	16.0	17.0	16.0	14.0	**13.0**	15.0	16.0	15.5	-0.48
Castellana	16.0	19.0	15.0	13.0	15.0	16.0	14.0	13.0	**12.0**	15.0	15.0	15.0	0.11
Plaza Castilla	16.0	14.0	14.0	15.0	13.0	17.0	11.0	13.0	**13.0**	14.0	16.0	15.0	2.24
Urb. Embajada	**14.0**	17.0	16.0	21.0	16.0	21.0	19.0	20.0	17.0	18.0	19.0	20.0	1.27
Sanchinarro	13.0	16.0	14.0	20.0	14.0	20.0	15.0	21.0	12.0	16.0	**12.0**	13.0	✓ -4.48
Tres Olivos	11.0	17.0	14.0	21.0	13.0	19.0	13.0	22.0	13.0	18.0	**10.0**	14.0	✓ -4.76
Escuelas Aguirre	19.0	16.0	20.0	17.0	18.0	19.0	18.0	15.0	**15.0**	18.0	19.0	18.0	-0.62

(Years span 2014–2019.)

The $PM_1$0 concentration in the air for the 12 sensed areas does not show a clear trend. Six of these 12 areas show the minimum concentration of of this pollutant during 2019 and five during 2018 (see Table 8). The concentration of $PM_1$0 during these two years (2018 and 2019) show similar lower distributions than the other periods of time (see Figure 16.c). When comparing `Pre-MC` and `Post-MC`, eight areas present a decrease on PM_{10} after the deployment of MC, five of which are statistically lower.

According to the results about the NO_2, $PM_{2.5}$, and PM_{10} concentration in the whole city of Madrid, the answer to **RQ3:** *Do pedestrianization policies in a given area of the city produce a pollution displacement to other zones of the city?* is that they do not produce pollution displacement. These pedestrianization policies positively impact on the whole city because there is a general reduction on the concentration of these three pollutants.

Finally, after the whole study we answer the **RQ4:** *Are smart city tools effective for evaluating urban health policies and other measures implemented in the city?*. As we have seen throughout the article, the application of smart city tools proves to be an effective way of assessing the effectiveness of measures against urban pollution. In this sense, the evolution towards the smart city would improve the local capacity to deal with the risks arising from rapid urbanization. The application of Internet Of Things to policy implementation allows us to avoid wrong, subjective or biased appraisal, offering an objective

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assessment of their effectiveness. Furthermore, the smart city paradigm proves to be the best way to monitor compliance with international emission requirements. However, we have faced the issue of dealing with non-homogeneous and incomplete data for our study. This may limit the outcomes of the analysis carried out: data analyses only can be as trustworthy as the data source. Thus, it is mandatory to provide a platform able to gather and share data complete and accurate.

6. Conclusions

The growth of car-oriented cities is raising new urban health problems resulting from the pollution increase. This requires quick responses to create sustainable environments from an environmental point of view. Several initiatives are being taken into account to address this challenge but some have been questioned in terms of their effectiveness. Smart city related technologies provide invaluable tools of analysis, helping decision making, and leading to the best outcome for the city. In this article, we evaluate the LEZ deployed in Madrid (Spain) applying smart city tools in order to objectively asses the reduction of the pollution of this measure and potential side-effects.

Real data provided by the Madrid City Council was processed to get time series of air pollutant concentrations and levels of noise in different areas of the city. According to the statistical and regression analyses, MC was able to significantly reduce NO_2 concentration locally, having the same positive impact in the rest of the city. In addition, it has been experienced a decrease in $PM_{2.5}$ and PM_{10} in most of the analyzed zones of the city. Thus, this LEZ effectively improves the air quality and it does not provoke border-effect. In terms of noise, this measure is able to slightly reduce outdoor noise levels, mainly the background ones generated by road traffic.

We found difficulties in terms of the quantity, quality, and reliability of the open data shared by the city council. Despite these limitations, smart city tools in Madrid have proved to be an invaluable resource to evaluate the effectiveness of this type of environmental measures.

The main lines for future work include extending the analysis performing a multivariate analysis by taking into account related data (e.g., wind speed, temperature, etc.); evaluating the impact on other relevant indicators (e.g., economical impact, mobility behavior, citizens' health, etc.); and applying other time series analysis methods and models (e.g., Markov Chains and recurrent neural networks) to characterize the pollution.

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Abbreviations

The following abbreviations are used in this manuscript:

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MC Madrid Central
LEZ Low Emissions Zone
TLA Three letter acronym
LD linear dichroism

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text. For example, explanations of experimental details that would disrupt the flow of the main text, but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

Appendix B

All appendix sections must be cited in the main text. In the appendixes, Figures, Tables, etc. should be labeled starting with 'A', e.g., Figure A1, Figure A2, etc.

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