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Car restriction policies for better urban health: a low emission zone in Madrid, Spain

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Abstract The design of most cities prioritizes the use of motorized vehicles, having a negative effect on urban health. A major concern in the European Union (EU) is air pollution, especially nitrogen dioxide (NO_2), which causes many inhabitants health problems and decreases the quality of life. A non-expensive way to reduce pollutants is implementing road restriction policies, as the creation of low emission zones. In this work, we analyze the case of Madrid Central a low emission zone deployed in Madrid, Spain. We evaluate if it was effective to reduce air pollutants and if there were a side effect, as pollution displacement, during its application. Drawing on open data, we analyze air quality at different points of the city, before and during the application of this measure. Taking into account the EU directives in terms of what healthy air means, we consider three metrics: a) the trend of NO_2 concentration in the air in both periods, b) the difference between the NO_2 concentration during both periods, and c) the percentage of time in which the population is exposed to air with NO_2 concentration under a specific threshold (healthy air as defined by the EU). According to the results, Madrid Central significantly reduces the NO_2 concentration in the air and does not produce pollution displacement. Thus, the population breathes healthy air during more time, and there is a positive effect on the whole city.

Keywords Urban Health · Low Emissions Zone · Pedestrianization · Air Pollution.

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Introduction

Urban concentration is the leading trend of nowadays societies; the amount of people living in urban areas is growing rapidly and is a worldwide phenomenon. Currently, 55% of the world's population lives in urban areas and it is expected to grow to 68% in the next fifty years (United Nations, 2018). Resulting from this concentration of inhabitants, new challenges and social problems have emerged, standing out the health risks. Air pollution, road traffic congestion, as lack of safe spaces for physical activity are contributing to rising death rates from stroke, heart disease, cancer, respiratory illnesses and injuries (World Health Organization, 2018b).

This is the undesired effect of an urban conceptualization which prioritizes the use of motorized vehicles, with different negative impacts over safety and reducing the quality of life. Nonetheless, a major concern derived from the rapid development of car-oriented cities is the high generation of air pollutants and their impacts on the citizens' health (Soni and Soni, 2016). Indeed, air pollution is the top health hazard in the European Union (EU) as it reduces life expectancy, provokes the loss of years of healthy life, and diminishes the quality of health (European Environment Agency, 2018; World Health Organization, 2018a).

As one of the major sources of pollutants in our cities is road traffic (Steele, 2001), reducing it would be an effective strategy to improve urban livability and their inhabitants' health. For example, several studies have proven that pedestrianization has a positive impact on health (Sobková and Čertickỳ, 2017; Soni and Soni, 2016; Tobon et al., 2018; Ward, 2010). Consequently, many cities have started to shift toward non-car friendly access (Parajuli and Pojani, 2018; Sobková and Čertickỳ, 2017; Tobon et al., 2018; Ward, 2010).

However, sometimes measures to reduce traffic can face strong resistance from economic and political agents. This is the case of *Madrid Central* (MC), a low emissions zone (LEZ) created in the biggest city of Spain, Madrid, which suffered a reversal after being questioned in terms of its results. MC consisted of limiting downtown access to the most polluting vehicles, and it was active just for a few months. After the city council elections, the new municipal government decided to reverse MC, accusing this measure of non-effective to reduce pollutants and of causing a *border-effect*. This effect refers to the risk of transferring emissions from one area to other closer areas by driving out unauthorized vehicles from the center of Madrid to those zones. Answering the question about if this reversal and political resistance was based on true evidence or not is the main goal of this study.

Previous works have shown that MC reduces air pollutants in the area of its application (Lebrusán and Toutouh, 2020; Toutouh et al., 2020). However, new questions arise from them that were not taken into account: *i)* if that reduction is enough in order to improve population health and, *ii)* which impact this reduction has on adjunct areas.

In this study, we focus on one of the air pollutants that has more impact on the inhabitants' health, nitrogen dioxide or NO_2 (Colvile et al., 2001; de Souza, 2019). This pollutant is directly related to many health hazards, such as asthma and obstructive pulmonary diseases, cardiovascular deaths, and infant and intrauterine mortality. It has been proven that most of NO_2 in cities comes from motor vehicle exhaust (up to 80%) (Department of the Environment and Heritage, 2005). Another important source of this pollutant is the electricity generation from coal-fired power stations.

As the main aim of this paper is to appraise the congruence of political resistance to the implementation of the measure in terms of its results, we address the following research questions: **RQ1:** *Are pedestrianization measures effective in reducing the concentration of NO_2 in the areas where they are applied?*; **RQ2:** *Does the LEZ impact on the health of the inhabitants in terms of the time exposed to healthier air?*; and **RQ3:** *What kind of influence does the application of pedestrianization measures have outside its area of influence?* Therefore, the main contributions of this work are: *i)* evaluate the environmental impact of the measures applied in the LEZ, *ii)* analyze the potential positive effect on urban health, and *iii)* assess the influence of pedestrianization policies out of the areas where they are applied.

The paper is organized as follows: The next section establishes the goals, strategies, and contextualization of the pedestrianization policy applied in MC. After that, the research methodology applied in this analysis is introduced. Then, the empirical evaluation of the air quality is shown. Finally, the conclusions and the main lines of future work are drawn.

Background

Prioritization of car use has had a huge impact on urban health, reason why international agencies are getting more involved in the reduction of air pollution. This section introduces the effect of car-oriented cities on urban health and analyzes the Madrid LEZ in the context of the EU clean-air directives.

Car oriented cities: the modern health risk

Air pollution is the top health hazard in the EU (European Environment Agency, 2018; World Health Organization, 2018a) as it reduces life expectancy, causes loss of years of healthy life, and diminishes the quality of health (Maciejewska, 2020). Just in the European Economic Area (EEA), it causes more than 400,000 premature deaths, being primarily associated with heart disease and strokes, followed by lung diseases and lung cancer (Brivio and Meder, 2019). Air pollution has been proved as carcinogenic even when isolating other factors (Raaschou-Nielsen et al., 2013). It reduces lung capacity, aggravates asthma, reduces lung functions, and is associated with chronic obstructive pulmonary diseases (Schraufnagel et al., 2019). Moreover, it provokes infertility and type 2 diabetes in adults, and it may be linked to obesity, systemic inflammation, aging, Alzheimer's disease, and dementia (Brivio and Meder, 2019).

The lack of clean air is creating a new dimension of inequality in terms of health vulnerability, presenting some population groups more susceptibility to adverse health effects (O'Neill et al., 2012). The effects are more dangerous over children, damaging their respiratory system permanently (Mehta et al., 2013; Siddique et al., 2011) and causing lower intelligence and delays in psycho-motor development (Rivas et al., 2019). Among pregnant women, it also has very negative consequences, reducing the transport of oxygen and nutrients to the fetus, and it may have effects on the speed of delivery (Mendola et al., 2019). Finally, the other age group most affected are the elderly, worsening preexisting conditions and shortening their lives. Besides, even short-term exposure to air pollutants increase respiratory disease (Simoni et al., 2015) and produces changes in the brain structure similar to those produced by Alzheimer's disease (Younan et al., 2020).

On top of this, the higher importance given to car use has had a negative effect on the quality of the urban public space, forgetting that the physical and spatial context influences people throughout the life course (Phillipson, 2011; Wahl, 2001). In fact, the design of cities during the first half of the 20th century prioritized the use of vehicles, forgetting so a large part of their citizens and their needs. The UN Committee on the Rights of the Child pointed out urban design and traffic in many cities among the main obstacles to fulfill the right of the child to play (article 31 of the Convention)(Assembly, 1989). The street is not a place to develop children activities anymore, due to traffic and lack of infrastructure for pedestrians (Mumford, 1946; Tonucci, 2005). This has an impact on the development of children's spatial awareness and their spatial activity, affecting children's social and physical development (Fotel and Thomsen, 2003). However, the biggest threat is air pollution, considered a *modern plague* (Goines and Hagler, 2007). In general, the importance given to motorized vehicles user had lead to a new form of vulnerability in cities, focused on those more dependent on urban design and more sensitive to pollution: children and the elderly.

An international approach to Urban Health Policies: the EU directives and Madrid Central

As a response to the air quality problems, the EU has adopted a number of environmental and health directives. The Clean Air Policy Package (CAPP) sets different objectives for 2020 and 2030 and 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 the vehicles. This package is based on `Directive 2008/50/EC` (European Commission, 2008) and `2004/107/EC` (European Commission, 2004).

The purpose of CAPP package is to safeguard EU citizens from environment-related pressures as well as risks to health and well-being. Furthermore, the pollution reduction would reduce also medical expenses: proper implementation of environmental legislation could save to the EU economy 50 billion of euros every year in health costs and direct costs to the environment (Brivio and Meder, 2019). Specifically, exposure to air pollution from road transport costs about 137 billion of euros per year in Europe (Book, 2014). Clean air can be considered a public good, but also a saving and investment plan.

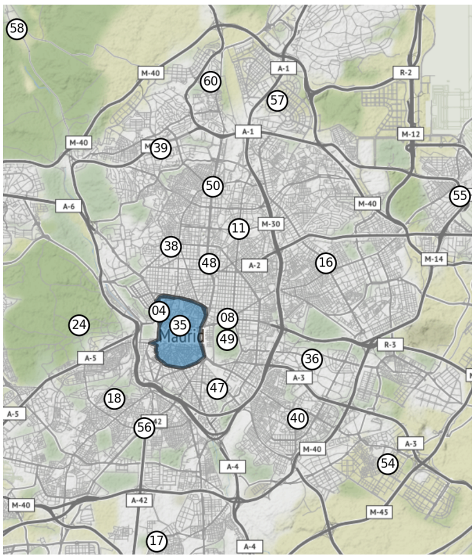
However, and even if there is an increasing public concern over health effects of air pollution (Dons et al., 2018), the measures are not always so welcome by the different member states. Thus, the EU demanded the reduction of these pollutants in the air under the threat of taking the case to the European Court of Justice, with the risk of important economic sanctions. According to the EU directives and the World Health Organization (WHO) recommendations, NO_2 concentration should be lower than 40 $\mu g/m^3$ to be considered healthy air. Nevertheless, several countries have exceeded repeatedly this NO_2 level, Spain among them.

As road traffic has been proved the biggest contributor to NO_2 (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2017), reduction of car use is revealed as one of the most effective strategies against emissions. Following this idea, the Madrid City Council designed MC. This is a LEZ in Madrid, consisting in car access restrictions in a delimited area of the downtown (see Fig. 1). This measure seeks to eliminate transit traffic, which crosses but has no origin or destination in MC.

Created by the *Ordenanza de Movilidad Sostenible* (October 5th, 2018), MC covers an area of 4,720,000 m^2. This is almost the entire *Centro* district, formed by the neighborhoods of *Palacio*, *Embajadores*, *Cortes*, *Justicia*, *Universidad*, and *Sol*. *Centro* district has 134,881 inhabitants, of which 12,377 are less than 17 years of age and 21,645 people are 65 years old or more. As we stated before, these age groups are more affected by pollutants and by the public space design.

While main goal of MC is reducing air pollutants, but also responds to the idea of introduce a new mobility behavior in the downtown. Nonetheless, it is primarily a measure to comply with the EU's requirements. The traffic restriction started on November 30th, 2018 while fines for noncompliance did not start until March 16th, 2019 facilitating the transition and adaptation. After barely some months of implementation, Spain avoided being brought before the European Court of Justice, paralyzing so the risk of fine.

However, and despite this successful result, after the elections (held on May 26th, 2019) the new government decided to apply a moratorium on fines from July 1st to September 30th, 2019 (art. 247 of the *Ordenanza de Movilidad Sostenible*). Neither the EU nor the inhab-



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

Fig. 1: Location of the sensors that gather the pollution information shared through the ODP. The shaded area illustrates the LEZ and the sensor at *Pza. del Carmen* (id. 35).

itants of the area were happy with the reversal, causing both a warning from the EU, and the emergence of citizen's movements claiming the continuity of MC. Vindicating in favor of urban health and the environment, some environmental groups filed a contentious-administrative appeal, and a judge provisionally paralyzed this reversal.

Research methodology

The primary goal of this study is to analyze the LEZ measure effectiveness to mitigate air pollution in the urban area of Madrid, and therefore, improve the health of its inhabitants. To this end, we focus specifically on the NO_2 concentration in the air, because of its pernicious effects on the population health. We have addressed such an analysis, first locally, evaluating the impact of the LEZ itself (at MC), and globally, by assessing the same in different areas of the city.

Madrid City Council installed 22 sensors (see Fig. 1) that gather data on the concentration of different air pollutants. These sensors hourly average this information and store it in a data bank, the Open Data Portal (ODP) of Madrid City Council (Madrid City Council, 2018). We use this platform to get the NO_2 concentration data analyzed here.

The analysis is performed considering a temporal frame of six years, from December 2013 to November 2019. Two time periods are distinguished: *Before-LEZ*, i.e., the five years before the implementation of MC (from December 2013 to November 2018), and *After-LEZ*, i.e., the period of one year after implementing the LEZ (from December 2018 to November 2019). The main idea is to compare both time periods to assess the effect of the measures applied in MC.

Three metrics are considered in the analysis:

– The NO_2 concentration itself during both periods in micro-grams per cubic meter ($\mu g/m^3$).
– The average difference between the NO_2 concentration during *Before-LEZ* ($x\widetilde{BLEZ}_m$) and *After-LEZ* ($x\widetilde{ALEZ}_m$) taking into account different periods of time (P). We denote this metric by $\Delta(P)$ (see Eq. 1) in which P is in order of months, days, and hours.
– The percentage of the time the population is exposed to air with NO_2 concentrations bellow to the threshold defined by EU during different periods denoted by $t_{NO_2<EU}(P)$.

The $t_{NO_2<EU}$ is important as it allows the evaluation of the effectiveness of improving population health, as there may be situations where the pollutant is reduced but the air is still unhealthy in terms of the evaluated pollutant (i.e. NO_2 concentration $> 40\ \mu g/m^3$).

$$\Delta(P) = \frac{1}{|P|} \sum_{m \in P} x\widetilde{BLEZ}_m - x\widetilde{ALEZ}_m \qquad (1)$$

In order to determine the statistical significance of the obtained results, Shapiro-Wilks statistical test was applied to check the normality of the distributions and Analysis of Variance (ANOVA) statistical models are applied to analyze the differences (as the results follow a normal distribution).

An evaluation of climate variables in Madrid during *Before-LEZ* and *After-LEZ* reveals that there are no noticeable differences in the weather of these two periods that may impact on the air quality results. The comparison of both periods in terms of temperatures, wind speed, and precipitations are illustrated in Figs. S1, S2, and S3, respectively.

Results and discussion

This section describes the experimental analysis carried out: first, we evaluate the air quality (NO_2 concentration) in the area where the LEZ is applied; second, we appraise the impact and the effectiveness of the LEZ at MC; and finally, we analyze the possible effect of this policy in the rest of the city.

Evaluation of the air quality at madrid central

The first step of our analysis involves evaluating NO_2 concentration data at MC (sensor id. 35). Monthly, seasonally, daily, and hourly analyses are performed to detect patterns and periodicity in the time series that represents the concentration of this pollutant. Fig. 2 summarizes the NO_2 concentration data by showing the mean values by months (the green lines illustrate the values after the application of the LEZ). The boxplot in Fig. 3 shows the NO_2 concentration at MC during the four seasons of the whole period of time analyzed. Fig. 4 illustrates the average values corresponding to the hourly NO_2 concentration for each day of the week.

Fig. 2 shows that most months before the measure application, mean NO_2 concentration was higher than the threshold established by the EU. This indicates the need for applying measures to reduce this pollutant in the air. Moreover, we observe that after the first three months of the development of the LEZ, the air pollutant starts to be lower than 40 $\mu g/m^3$. Finally, the temporal pattern in the NO_2 concentration reveals that autumn and winter months are more polluted than spring and summer ones.

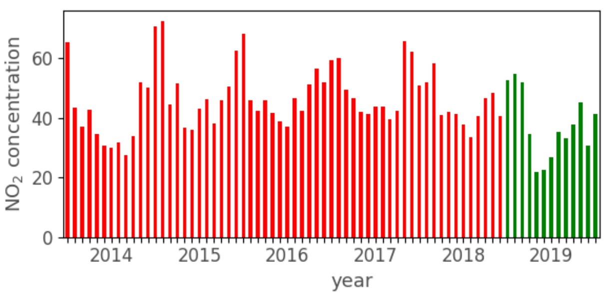


Fig. 2: Mean NO_2 concentration per month.

Fig. 3 confirms that warmer seasons have better air quality. This is attributed both to 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 longer in the air in winter (Chen et al., 2015).

As most of the pollution is due to transit road traffic in MC, Fig. 4 illustrates that the days from Monday to Friday (working-days in Madrid) experience a morning peak of NO_2 concentration and a late afternoon one. These are the hours with heavier road traffic in Madrid. However, the early morning peak does not appear during the weekends. These peaks lead to the pollutant to overcome the EU threshold.

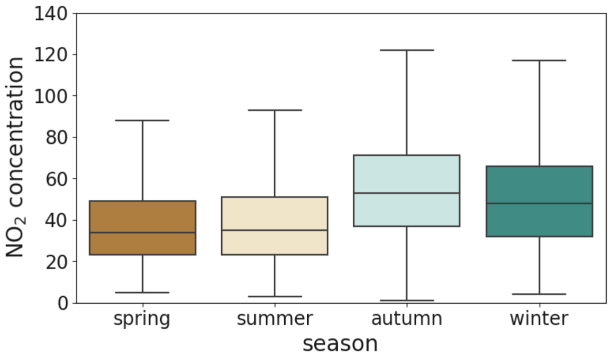


Fig. 3: NO_2 concentration per hour for each season.

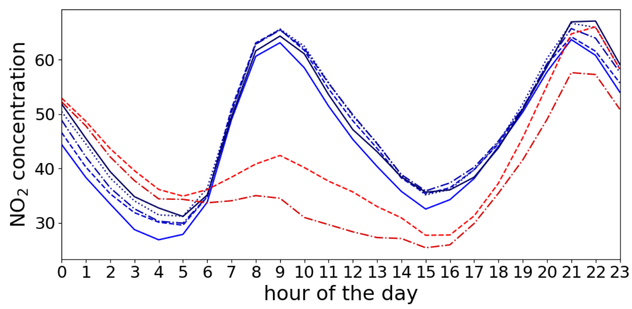


Fig. 4: Mean NO_2 concentration per hour for each day of the week.

Figs. 5 and 6 show the average NO_2 concentration higher than 40 $\mu g/m^3$ throughout the day for working-days and weekends, respectively. During working-days, the population is exposed longer to unhealthy air. Therefore, policies and measures against urban pollution need to be more effective on workdays.

Table 1: Summary of the NO_2 concentration (in $\mu g/m^3$) (gathered by sensor id. 35). Negative values of Δ indicate a reduction of NO_2 concentration.

Day type	*Before-LEZ*			*After-LEZ*			Δ
	Min	Mean±Stdev	Max	Min	Mean±Stdev	Max	
Spring							
working-day	5.00	40.62±50.43%	144.00	1.00	25.29±66.08%	131.00	-15.33
weekend	5.00	32.79±57.04%	162.00	1.00	20.47±73.38%	101.00	-12.32
Summer							
working-day	3.00	41.99±53.45%	196.00	9.00	36.07±54.15%	139.00	-5.93
weekend	5.00	34.27±65.72%	194.00	8.00	29.94±62.06%	116.00	-4.34
Autumn							
working-day	1.00	58.52±46.31%	224.00	5.00	44.62±54.49%	123.00	-13.90
weekend	6.00	50.86±45.77%	170.00	5.00	34.46±61.85%	122.00	-16.40
Winter							
working-day	4.00	52.87±49.09%	196.00	1.00	51.62±52.21%	147.00	•-1.26
weekend	8.00	46.53±50.44%	194.00	5.00	44.34±50.65%	110.00	•-2.19

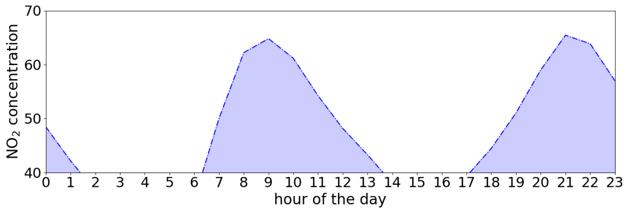


Fig. 5: The shaded area represents the NO_2 concentration over the EU threshold during working days.

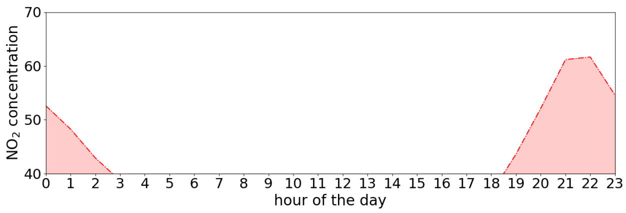


Fig. 6: The shaded area represents the NO_2 concentration over the EU threshold during weekends.

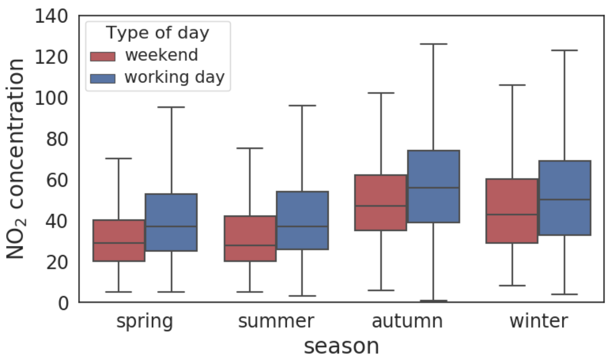


Fig. 7: NO_2 concentration per hour grouped by season and type of day.

The effect of the LEZ on air quality

According to the different time patterns shown by the concentration of NO_2, we evaluate the impact of the application of the LEZ by taking into account the seasons and the day type (weekday or weekend) in the comparisons. Fig. 7 illustrates the data according to these criteria.

Table 1 reports the values for NO_2 concentration in $\mu g/m^3$ before and after installing the LEZ. Minimum (*Min)*, mean, normalized standard deviation (*Stdev*), and maximum (*Max*) values are reported. The Δ column reports the average difference between *Before-LEZ* and *After-LEZ* values (negative value indicates reduction). The black dot (•) in the last column indicates that there is no statistical difference between *Before-LEZ* and *After-LEZ* values according to ANOVA.

Regarding the results in Table 1, there are significant differences between the NO_2 concentration during the period before the application of LEZ and after for all seasons but winter. For spring and summer, the LEZ allows working-days to satisfy the EU threshold on average, which was not occurring before. In autumn, the reduction is higher than in summer, however, the average is still higher than the EU threshold. Finally, although there is a reduction in the concentration of the pollutant in winter, there is no significant difference between the two periods.

As a consequence, the answer to **RQ1:** *Are pedestrianization measures effective in reducing the concentration of NO_2 in the areas where they are applied?* is yes, because the NO_2 concentration in the air is statistically lower after the application of the LEZ.

Table 2 shows Δ (the same in Table 1) and the percentage of time (evaluating hourly data) that the NO_2 concentration is bellow the EU threshold for both, *Before-LEZ* and *After-LEZ*. This allows us to discuss the amount of time the population is exposed to air considered healthy by the EU threshold (in terms of NO_2 concentration), because it may be used as a magnitude of their quality of life with this regard.

Table 2: Percentage of time (%) with NO_2 concentration bellow the EU threshold. Larger percentage represents healthier environments.

Day type	Δ	*Before-LEZ* (%)	*After-LEZ* (%)
		Spring	
working-day	-15.33	54.89	82.77
weekend	-12.32	74.25	90.22
		Summer	
working-day	-5.93	54.35	67.99
weekend	-4.34	71.91	77.88
		Autumn	
working-day	-13.90	25.84	48.24
weekend	-16.40	34.49	67.15
		Winter	
working-day	-1.26	34.03	34.44
weekend	-2.19	44.15	43.75

After the application of LEZ, the amount of time in which the population benefits from healthy air increases in all seasons, but weekends in winter.

In autumns, this time is practically duplicated for both, working-days and weekends. The improvement in spring leads to having about 90% of the time the air satisfying the EU threshold. As the pollution may not be provoked by the road traffic in winter, it seems that the LEZ is not enough to deal with this situation. Thus, other measures (not related to road traffic) should be considered to address urban air pollution.

According to these results, the answer to **RQ2:** *Does the LEZ impact on the health of the inhabitants in terms of the amount of time exposed to healthier air?* is yes: the population benefits from clean air during a longer time. This improvement is mainly due to the change of the mobility patterns of the inhabitants, which cease using private vehicles to cross MC area. This reduction of the traffic volume in the LEZ continues even when fines were withdrawn, but to a lesser extent (see Fig. S4).

Indirect effect on the rest of the city

The application of this type of policy has effects on the mobility patterns of the inhabitants in the whole city (Soni and Soni, 2016), and therefore, it impacts on the pollution level in different areas of the municipality. Here, we study the NO_2 concentration measured by sensors located throughout Madrid (see Fig. 1). In this section, we evaluate the difference in the concentration of this pollutant between the two periods (i.e., Δ) and the percentage of the time in which air quality meet the EU threshold.

Table 3 shows results of Δ taking into account the day type and without this distinction (*Overall*) for all the sensors. The shaded row represents the results in MC. Table 4 contains the percentage of time (hourly) the NO_2 concentration is below the EU threshold, i.e., the population breathe a healthy air. We take into account *Before-LEZ* and *After-LEZ* periods, working-days, weekends, and without this distinction (*Overall*).

Table 3: Values of Δ for working-days, weekends, and without taking into account the type of day, in all the sensors of Madrid. Negative values of Δ indicate a reduction of NO_2 concentration.

Station	working-day	weekend	Overall
Pza. de España	-6.72	-2.71	-5.58
Escuelas Aguirre	7.27	8.89	7.73
Avd. Ramón y C.	-4.13	• 0.40	-2.83
Arturo Soria	-5.11	• -0.51	-3.80
Villaverde	-3.63	• -0.73	-2.80
Farolillo	-5.27	-2.45	-4.46
Casa de Campo	-1.54	• -0.34	-1.20
Pza. del Carmen	-9.53	-8.86	-9.34
Moratalaz	-3.01	0.61	-1.97
Cuatro Caminos	-4.70	• -1.55	-3.80
Barrio del Pilar	-5.41	• -0.43	–3.98
Vallecas	-4.03	• -0.50	-3.02
Mendez Alvaro	-4.45	• -1.61	-3.64
Castellana	-4.04	• -1.01	-3.17
Par. del Retiro	-5.22	-3.34	-4.69
Plaza Castilla	-6.27	• -1.53	-4.92
Ens. de Vallecas	• -1.52	2.24	-0.45
Urb. Embajada	-4.99	0.63	-3.39
Pza. Elíptica	-2.38	• 0.59	-1.53
Sanchinarro	-2.31	1.82	-1.13
El Pardo	• -0.59	0.67	-0.23
Tres Olivos	-11.03	-4.29	-9.10

According to the results in Table 3, there is a reduction in the average NO_2 concentration for all the sensed areas during working days, except at *Escuelas Aguirre*, which experiments an important increase. For the weekends, the behavior is different. The pollutant is reduced to a lesser degree than on working days, there are some minor increases (between 0.40 and 1.82 $\mu g/m^3$), and in half of the cases, the differences are not statistically significant. The overall Δ values indicate that there is a general reduction of the NO_2 concentration, but the referred situation at *Escuelas Aguirre*.

Table 4: Percentage of time with NO_2 concentration bellow the WHO threshold (%). Larger percentage represents healthier situations.

Station	*Before-LEZ*			*After-LEZ*		
	working-day	weekend	Overall	working-day	weekend	Overall
Pza. de España	44.06	60.15	48.65	54.27	62.95	56.75
Escuelas Aguirre	45.87	65.15	51.38	33.85	55.38	40.00
Avd. Ramón y C.	47.43	71.40	54.28	54.52	71.19	59.29
Arturo Soria	55.41	74.23	60.79	62.93	73.96	66.08
Villaverde	54.66	67.27	58.26	59.17	67.03	61.41
Farolillo	57.77	69.51	61.12	64.19	71.63	66.32
Casa de Campo	78.76	86.65	81.01	80.30	87.18	82.26
Pza. del Carmen	41.40	56.04	45.58	58.36	69.75	61.61
Moratalaz	55.58	72.98	60.55	60.23	70.91	63.28
Cuatro Caminos	49.62	68.33	54.96	57.78	70.50	61.42
Barrio del Pilar	55.03	71.55	59.75	62.44	69.79	64.54
Vallecas	55.40	72.10	60.17	60.51	71.79	63.73
Mendez Alvaro	57.24	71.12	61.21	62.57	72.53	65.42
Castellana	52.99	74.03	59.00	61.08	74.12	64.80
Par. del Retiro	68.15	80.64	71.72	73.01	82.57	75.74
Plaza Castilla	45.54	69.17	52.29	57.62	72.64	61.91
Ens. de Vallecas	59.48	74.85	63.87	60.94	72.84	64.34
Urb. Embajada	50.06	63.58	53.92	56.31	62.30	58.02
Pza. Elíptica	32.49	50.48	37.63	36.05	49.70	39.95
Sanchinarro	65.72	80.24	69.86	69.74	77.24	71.89
El Pardo	90.26	95.85	91.86	91.47	95.71	92.68
Tres Olivos	63.14	78.96	67.66	79.24	85.02	80.89

The non-reduction of NO_2 in *Escuelas Aguirre* is mainly because the air quality sensor is installed in the exit of a tunnel located between *Alcalá* and *O'Donnell* streets. This point is the main connectivity node of entrance in Madrid for populations from southern neighborhoods and suburbs. There is also a greater influx of heavy vehicles (such as trucks), which are more polluting. The road traffic volume of this road increased after the deployment of the LEZ (see Table S1). Reducing emissions in this area would require specific measures.

As expected, another important reduction is given at the area sensed by sensor 4 (*Pza. España*), which is the closest sensor to the MC area. It experiences a reduction in the NO_2 concentration of 5.58 $\mu g/m^3$.

The results in Table 4 indicate that, in general, the air is healthy during longer periods after the LEZ policy was applied for all the sensors, except at *Escuelas Aguirre* (see Overall columns in Table 4). During the working-days, these improvements are higher than during weekends.

According to these results, the answer to **RQ3:** *What kind of influence does the application of pedestrianization measures have outside its area of influence?* is the pedestrianization policies positively impact on the whole city because there is a general reduction on the NO_2 concentration and an increase on the time exposed to healthy air.

As a general remark, the MC improves the health of the inhabitants that live in the LEZ area and it has a side positive impact on reducing NO_2 in the whole city. The principal reason is that the application of this measure arises a change in the mobility patterns of the population. As can be seen in Table S1, the areas evaluated in this study, in general, reduce their road traffic density after the deployment of the LEZ.

Conclusions and future work

The quickness of the urbanization process brings new health risks for which some population groups are more vulnerable than others. One of the most important duties for local governments is to take action and fight against these hazards, like pollution, in order to improve urban health.

Here, we analyze the real effect of one measure applied to reduce pollution in Spain: Madrid Central (i.e., the implementation of a LEZ). We use open air-quality data to evaluate its effectiveness in terms of environmental benefits and its potential effects on health. Despite the short lifespan of MC, and according to the analysis carried out, this LEZ had a positive effect on urban health for several reasons: *i)* there was a demonstrated lowering of NO_2 concentration, *ii)* during the LEZ application the population breathed healthy air during more time, and *iii)* there was a proved positive effect not just in MC area but in the rest of the city.

Besides, the reduction of car use in MC and in areas nearby indicates the effectiveness in changing the mobility behavior of the inhabitants. We understand that

MC is a successful precedent in this regard. The compliance of the measure, even when fines are withdrawn, allows venturing that inducing changes in mobility behavior is possible through measures like this one. Also, we can infer that some awareness is being created on the health and environmental risk of car emissions.

Another point we would like to stress is that the increase of NO_2 in *Escuelas Aguirre* may be signaling that the tunnel ventilation system is not providing enough clean air to protect drivers' health. It would be necessary for the city council to carry out specific measures to address such issue.

While there was not a border effect (or pollution displacement), in order to improve urban health, two phenomena need bigger attention:

- The season effect: During winter, pollution emissions from sources other than road traffic increase, reason why other complementary measures would be needed to improve urban air quality.
- The day of the week effect: According to the results, the pollution problem is smaller during the weekends, which points to the need for additional measures for the working days.

While this research proves the effectiveness of MC, the future research lines are: *i)* analysis of the effect of MC in noise reduction, as this is another major problem affecting the population in the EU; *ii)* comparison with other case studies in order to understand which measures are having better results in terms of urban health; and *iii)* evaluating the impact of pedestrianization measures on health indexes.

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