Were traffic restrictions in Madrid effective at reducing NO2 levels?

Rafael Salas
Universidad Complutense de Madrid and ICAE, Campus de Somosaguas, 28223 Madrid (*Spain*).
E-mail: r.salas@ucm.es

Maria J. Perez-Villadoniga
Universidad de Oviedo. E-mail: mjpvilla@uniovi.es

Juan Prieto-Rodriguez
Universidad de Oviedo. E-mail: juanprieto@uniovi.es

Ana Russo
Instituto Dom Luiz, Universidade de Lisboa. E-mail: acrusso@fc.ul.pt

(ACCEPTED VERSION)

Abstract

In this paper we assess the effectiveness of the introduction of Madrid Central (MC), a low-emission zone (LEZ), to improve air quality in the centre of Madrid. We take advantage of this policy change to identify the effect of the application of a LEZ on NO_2 concentrations. The bottom line is that our findings provide evidence that the introduction of Madrid LEZ has had a positive impact on reducing NO_2 emissions, as measured by Plaza del Carmen's monitoring station. Furthermore, monitoring stations nearby Madrid LEZ also exhibit significant, though smaller, reductions in NO_2 levels. These results suggest that there was a positive *spillover* effect and that pollution was not transferred from the city centre to other nearby areas. Instead, it seems that citizens in Madrid actually changed their transportation habits.

Keywords: Low emissions zones effectiveness; air quality; NO_2 emissions; pollution control

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1. Introduction

There is a great concern about the impacts of air pollution both among the general public and policy makers. Air pollution affects negatively not only the environment (e.g. acid rain, haze) but also human health, through respiratory and cardiovascular disease (Chiusolo *et al*., 2011; Santurtún *et al*., 2017) as well as cancer development (Vineis *et al*., 2006). It is also one of the main causes of premature deaths due to environmental factors throughout the world (Lim *et al*., 2012; Babatola, 2018). The European Environment Agency (EEA, 2017) estimates more than 400,000 early deaths in the European Union (EU) per year due to air pollution. This obviously imposes a high cost on society, also in pecuniary terms, with costs related to health estimated by the European Commission in the range of 330-940 billion euros per year. Pollution costs also include costs to the economy in terms of productivity losses, as the annual number of lost workdays in Europe due to air pollution is calculated to be above 100 million per year, according to this report of the EEA. This problem is especially important in cities, where most of the world population lives. Accordingly, actions taken in order to reduce traffic congestion or air pollution are becoming more frequent, namely the creation of low-emission zone (LEZ) areas.

This policy is not an isolated initiative but has to be understood as one of the many programmes that different cities in Europe have undertaken in the last years in order to fulfil European Commission (EC) standards. To cope with the health problems derived from poor air quality in all Member States, the Ambient Air Quality Directives (Directive 2008/50/EC and Directive 2004/107/EC) established temporary limits for various pollutants, such as nitrogen dioxide (NO_2), which is one the most harmful pollutants in the air (Izquierdo *et al.*, 2020). Member States were allowed to choose the means to comply with the limit values agreed at the EU level and were required to adopt Air Quality Plans when these limit values were exceeded. These limits are enforced under severe fine schemes to the non-compliant countries. Hence, following the EU recommendation, many European cities, such as Amsterdam, Berlin, Milan, London or Madrid have adopted LEZ policies, although with different levels of restriction.

Indeed, LEZs have broader public policy implications that can make implementation difficult. For instance, low-income households and small and medium enterprises that need to use their vehicles within the LEZs and could not afford a switch to clean alternatives, need exemptions and financial support schemes (European Federation for Transport and Environment, 2020). If policymakers do not establish an adequate support programme, public citizen opposition will make it difficult to implement such traffic restrictions.

Moreover, should LEZs become zero-emission mobility zones (ZEZ) in the future, policies promoting a switch to clean alternatives (e.g. walking and cycling or the electrification of all transport modes) would be more important (EP, 2020). This transition would also require a complete phase-out of internal combustion engines by the mid-2030s, as is already planned in some countries, such as the UK or Germany. Research evidence can allow the identification of gaps in the implementation of air quality policies and better air quality management plans.

In this paper we analyse the particular case of Madrid, where local authorities opted for a LEZ approach, called Madrid Central (MC). This approach prevents pollutant vehicles from entering an area of 4.7 km2 in the city centre coming into force on December 1, 2018. Compared to other initiatives, Madrid Central is probably one of the most ambitious traffic pollution policies since banned vehicles cannot access the area, not even paying an entrance fee. To put this LEZ in context, Madrid is the third Europe's largest metropolitan area, with almost 6 million inhabitants (and more than 3 million in the municipality). It has a highly developed transport network infrastructure, which includes highways and a widely used public transportation system comprising the underground network (293 km long), the local commuter train (370 km) and a dense network of bus routes. Every day 3/4 of a million commute to work, relying on their individual cars or public transportation (Baldasano, 2020). Regarding the emission patterns of Madrid, traffic and the airport are the two most predominant emission sources of primary pollutants (Guevara et al., 2013). Therefore, fossil-fuel combustion by-products, namely NO2, are especially relevant for this city as they constitute a significant threat to human health (Fuertes et al., 2016; Min and Min, 2017; Pujol et al., 2017).

However, perhaps due to its recent implementation, studies on MC effectiveness are still scarce (e.g. Izquierdo et al., 2020). Conversely, evidence is available for other cities, namely Panteliadis *et al*. (2014) for Amsterdam; Carslaw *et al*. (2016) for London or Wolff (2014); Lutz (2009) for Berlin, Malina and Scheffler (2015), Gehrsitz (2017) for German cities. Thus, our analysis complements the existing literature on LEZ throughout

Europe, contributing to the debate on the design and options of air pollution regulations. Moreover, Madrid Central is an example of a quite restrictive LEZ, that required very difficult political negotiation and was under continuous political scrutiny. In fact, it was central to the political debate during the subsequent election campaign. In this sense, proving the effectiveness of ambitious initiatives in reducing pollutant levels can be relevant to guide future and ongoing political debates to approve new LEZ or, especially, to tighten existing ones.

In order to achieve the proposed goal, we analyse the impact of the implementation of MC LEZ on NO_2 emissions in the urban area of Madrid between the 1st of December 2018 and the end of May 2019, since the programme was partially modified by the change in the Madrid municipality governance. We perform a difference-in-difference (Diff-in-Diff) analysis to evaluate the effectiveness of this policy, similar to that performed by Wolff (2014), Gehrsitz (2017) and Li *et al*. (2019). Additionally, to take into account a possible spillover effect, we use data from monitoring stations not only within the LEZ, but also from surrounding areas, which could have been affected by those motorists who decided to drive longer routes outside of MC LEZ once it came into force.

The paper is structured as follows. In Section 2 we briefly review the literature. Section 3 describes the main features of Madrid Central. Data are presented in Section 4. The empirical specification is described in Section 5 and results are discussed in Section 6. Finally, Section 7 concludes.

2. Background

Despite improvements in the quality of air in the EU over the last decades, air quality standards have not been met yet. In view of this situation, the EU has passed legislation with the aim of achieving levels of air quality that do not cause negative impacts on human health and the environment. The Ambient Air Quality Directives establish air quality standards, which in the case of NO_2 (Directive 2008/50/EC) set an annual limit of 40 µg/m3. Whenever the limit values are exceeded, countries are required to adopt air quality plans specifying measures to keep the exceedance period as short as possible.

To meet the air quality requirements, many European cities have established different kinds of LEZs, with different levels of restriction and rules to access the restricted area.

The first LEZs in Europe were introduced in Sweden in 1996 for heavy duty vehicles driving into Stockholm, Goteborg and Malmo city centres. Since then, many European cities have adopted LEZs and currently there are over 250 LEZs in Europe.

Most of the literature is related with the study of a particular LEZ, with London being the most extensively analysed (Holman *et al*., 2015). In this city, a Congestion Charging Scheme was first introduced in 2003. Motorists travelling through London city centre during peak hours had to pay a daily charge. In 2008, a Low Emissions Zone, operating 24/7 in Greater London, was set up and high emission commercial vehicles were required to pay an additional charge.[1] Empirical evidence on the effectiveness of this LEZ on NO_2 concentrations is not conclusive. While Ellison *et al*. (2013) find no significant changes in NOx concentrations, Carslaw *et al.* (2016) conclude that NO_2 concentrations decreased since 2010.

In the case of Amsterdam, a LEZ was first introduced in 2006 for heavy-duty vehicles based on their emission category that came fully into force in 2009. Since 2010, regulations have gradually tightened over time. Using data for the period 2007-2010, Panteliadis *et al*. (2014) find that the implementation of Amsterdam LEZ led to lower traffic-related air pollution, with NO_2 concentrations reduced by 4.9%.

Berlin was one of the first cities in Germany to establish a LEZ which was set up in two stages, the first in 2008 and the second in 2010. To enter the zone, all vehicles must fulfil certain emission standards and display the appropriate sticker. During the first year of operation of the LEZ, Lutz (2009) estimates that NO_2 concentrations decreased by 8%. More recently, Jiang *et al*. (2017) find positive effects on air pollutant concentrations due to the implementation of different LEZs across Germany, but limited evidence of reductions in NO_2 concentrations. As the authors claim, these mixed results may be due to the fact that LEZ effects are often confounded with the impact of other measures implemented at the same time.

In summary, most of the empirical analyses that measure the effectiveness of LEZs find a positive effect in reducing air pollution concentrations (e.g. Lutz, 2009; Panteliadis et al., 2014; Wolff, 2014; Holman *et al*., 2015; Malina and Scheffler, 2015; Gehrsitz, 2017; Jiang *et al*., 2017; Li *et al*., 2019). Obviously, the effectiveness of a LEZ is likely to be

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[1] More recently, to comply with the EU legal limits set on NO_2, the Ultra-Low Emissions Zone (ULEZ) was implemented in April 2019. All vehicles need to meet ULEZ emission standards or pay an additional daily charge to travel within Central London.

determined largely on how well it has been designed. In a review of studies on the efficacy of LEZs in five EU countries, Holman *et al.* (2015) find that reductions in average PM_{10} and NO_2 are larger for LEZs imposing restrictions on both passenger cars and heavy duty vehicles compared to those only affecting heavy duty vehicles. The authors claim that more sophisticated statistical models should be used to control for confounding factors, such as other public policies or meteorological variables. In fact, according to the environmental engineering literature, urban air pollution is constrained by a combination of factors, namely, pollutants' emissions, physical boundaries and meteorological conditions (e.g. Demuzere *et al.*, 2009). Thus, daily meteorological factors should be accounted when addressing short-term air pollution variability (Russo *et al.*, 2013; Seo *et al.*, 2018).

3. **Madrid Central**

Madrid Central (MC) is a low-emission zone which aims to prioritise public transportation, electric and hybrid vehicles and bicycles and pedestrians. Residents can drive and park without restrictions in the city centre; non-residents are allowed to enter the area only if their vehicle is electric or certified as non-polluting. Drivers who do not comply with the rule can be fined 90 euro.

The decision of establishing this LEZ in the centre of Madrid was related to the bad quality of the air in the area. Not a single value below the annual 40 μg/m3 limit has ever been reported since the eighties for Plaza del Carmen, the only monitoring station of environmental pollutants in the MC area. These high levels of NO_2 emissions in Madrid were one of the reasons why Spain was one of the candidate countries to be penalized by the EU.

Supporters of MC argue that, since the program started, traffic congestion has been reduced, pollution levels within the city centre have fallen and the use of public transport has increased. Conversely, opponents argue that MC shifted traffic congestion and pollution to peripheral areas and that it has had negative economic effects, as many businesses in the city centre were hurt. However, most of these arguments can be labelled as mere opinions since they are not based, as far as we are aware, on scientific analyses.

Moreover, weather conditions during the first four months after the implementation of MC have not worked in its favour. The State Meteorological Agency (AEMET) stated that, between December 2018 and February 2019, there were 42 days with *unfavourable weather* conditions, more than doubling the number of *unfavourable* days in the same period the previous year (Ecologistas en Acción, 2019). Actually, in the winter months of 2018-2019 (December-February), the average sea level pressure and geopotential were, respectively, 2.9 hPa and 216 m higher, while the wind intensity was 3.2 km/h lower than in the same three months of the previous three years. Since certain weather conditions (high pressure/geopotential, low wind intensity) tend to increase pollution (de Nevers, 2000), this may have led to erroneous conclusions regarding the effectiveness of MC. Therefore, it is vital to assess meteorological conditions, as well as any other confounding factor, to accurately evaluate the effectiveness of the implementation of any LEZ, such as MC.

4. Data

For the analysis of MC effectiveness, we consider the whole air quality monitoring network of Madrid municipality which nowadays comprises 24 monitoring stations, and was designed to supplement EU Directive 2008/50/EC. Since Madrid municipality (darker area of Figure 1, covering 605.8 km^2) goes far beyond the limits of Madrid city, its monitoring network includes 3 suburban stations and 21 urban stations, some of them located outside Madrid city in what were former independent municipalities. These urban stations are classified in 9 specific traffic stations (roadside stations that measure pollutants from nearby traffic) and 12 background stations (representative of a wider area measuring pollutants of all sources). In order to define the control stations, we additionally consider 17 (non-rural) remote stations belonging to Madrid autonomous community network, i.e., located in other areas within Madrid region. Altogether, these 41 stations cover far beyond the defined Madrid metropolitan area, encompassing an area of 1935.97 km^2.

Figure 1. Madrid: municipality, metropolitan area, and region

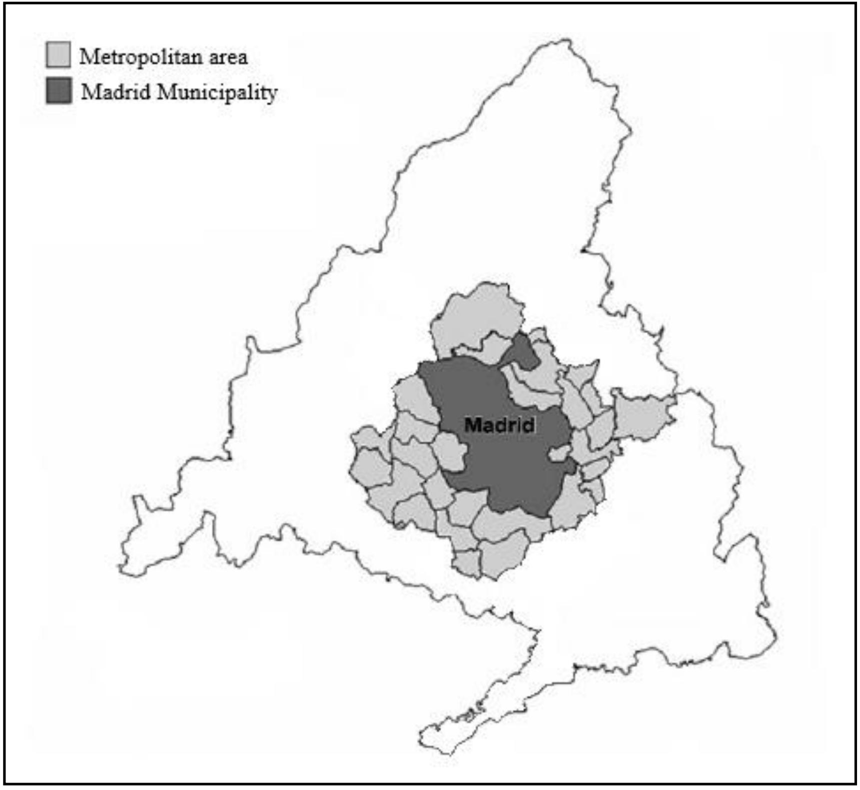

Figure 2 shows the stations considered, and their location within the Madrid region. The concentric black boundaries represent, respectively, the MC LEZ limit, the M30 ring road and the limits of the Madrid municipality. Plaza del Carmen (PC) is the only station within the Madrid LEZ. Therefore, in terms of the usual terminology of the Diff-in-Diff models, Plaza del Carmen is our "treatment" station.

Note that some stations in the city of Madrid may have been potentially affected by the implementation of the LEZ to a different extent. Therefore, we define different groups of stations, according to the distance to the "treated" station, in order to take possible *spillover* effects into account. First, the *surrounding stations* include Plaza de España (PE), Escuelas Aguirre (EA), Mendez Alvaro (MA) and Parque del Retiro (RE), i.e., the four closest monitoring stations to Plaza del Carmen. Second, we consider three consecutive station "belts". The *First Belt*[2] includes other stations inside the M30 ring

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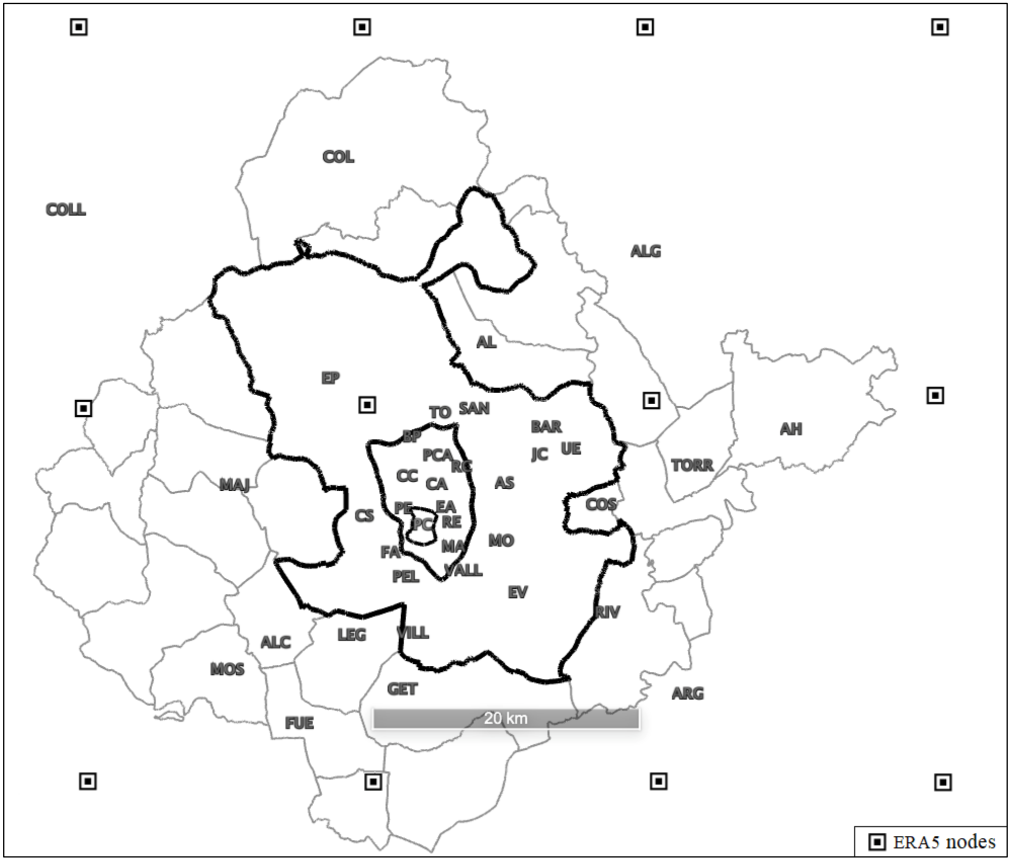
[2] Includes Plaza Castilla (PCA), Castellana (CA), Barrio del Pilar (BP), Cuatro Caminos (CC) and Ramon y Cajal (RC).

road, but further away from Madrid Central. The *Second Belt*[3] comprises stations that are close but outside the M30 ring road and the *Third Belt*[4] includes stations outside and not near the M30, but still within the Madrid municipality although relatively far from the city itself. The remaining 17 (non-rural) stations in the metropolitan area or beyond, are located so far that they should not be affected by the application of the policy, and, thus, are the ultimate "control" group.[5]

Figure 2. Location of the air quality monitoring stations and Madrid Central LEZ



Note: There are 2 control stations not included in this map, both located to the south: Valdemoro, at 30 km, and Aranjuez, at 55 km.

In this paper, we use daily official NO_2 level data obtained from the Madrid municipality and Madrid autonomous community networks from December 2015 to May 2019.

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[3] Includes Arturo Soria (AS), Farolillo (FA), Moratalaz (MO), Vallecas (VALL), Plaza Eliptica (PEL), Sanchinarro (SAN) and Tres Olivos (TO).

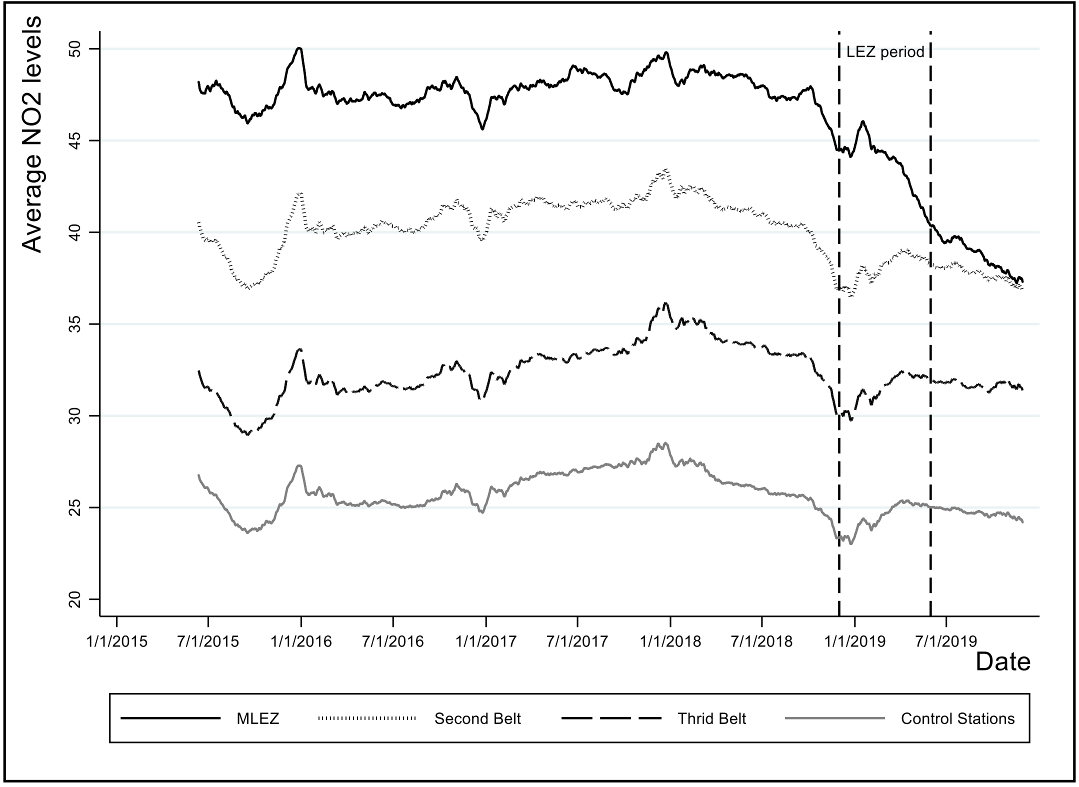
[4] Includes Villaverde (VILL), Casa de Campo (CS), Barajas (BAR), Ensanche de Vallecas (EV), Urbanizacion Embajada (UE), El Pardo (EP) and Juan Carlos I (JC).

[5] Includes non-rural stations outside the municipality of Madrid: Alcala de Henares (AH), Alcobendas (AL), Algete (ALG), Arganda del Rey (ARG), Coslada (COS), Rivas-Vaciamadrid (RIV), Torrejon de Ardoz (TORR), Alcorcon (ALC), Aranjuez, Fuenlabrada (FUE), Getafe (GET), Leganes (LEG), Mostoles (MOS), Valdemoro, Colmenar Viejo (COL), Collado Villalba (COLL) and Majadahonda (MAJ).

Average daily NO_2 levels were calculated for those stations that reported at least 18 hourly data for that particular day.

In Figure 3, we display the evolution of annual means of NO_2 concentrations for Plaza del Carmen and the three farthest station groups (*Second Belt*, *Third Belt* and control stations), constructed as a past-yearly moving average (the unweighted mean of the previous 365 days). Vertical lines indicate the period while MLEZ was in force. By excluding the closest stations to Plaza del Carmen we want to ignore, at this stage, potential treatment spillovers, i.e. changes in pollution in nearby stations due to the treatment of the treated unit. In some way, we want to check whether outside Madrid municipality stations can be considered as good control stations.

Figure 3. Moving average of daily NO_2 concentrations for Plaza del Carmen and surrounding air quality stations



While there is some variation, inspection of the graph suggests that the closer we move to the centre, the higher the average levels of pollution, although following a common trend. This common trend is also observed for Plaza del Carmen before the introduction of the traffic restrictions. However, the implementation of the policy leads to a deviation from this trend, resulting in a significant reduction of NO_2 levels.

There is a substantial sharp reduction in NO_2 that occurs just prior to the policy implementation, as displayed in Figure 3. This drop seems to be common to all the areas considered, does not affect the joint trend and, could be associated, as mentioned in the last paragraph of Section 3, to a beneficial climatic year (Ecologistas en Acción, 2019). Also, between April and November 2018, a large public works plan took place. Within this plan, and especially relevant for our study, is the comprehensive remodelling of Gran Via, the main avenue that crosses the LEZ. This avenue was completely refurbished, reducing the number of traffic lanes in both ways, with severe traffic restrictions during the works, that ended, however, just three weeks before the entry into force of the LEZ restrictions.

Table 1 exhibits the evolution of the traffic flows in Madrid Central and surrounding stations areas, as well as in the rest of the city. These values are influenced by seasonal variations and other factors, such as differences in rainfall or tourism flows, which can affect driving and transport decisions. These factors also include public works, public transportation strikes and traffic regulations. Although we observe nothing but seasonal variations during 2016 and 2017, there is a notable drop in the traffic flows within the Madrid Central area since the first quarter of 2018. This fall took place during the remodelling of Gran Via and continued once it was completed but Madrid Central was in place. This falling trend is also observed in the other areas, but it is less pronounced in relative terms.

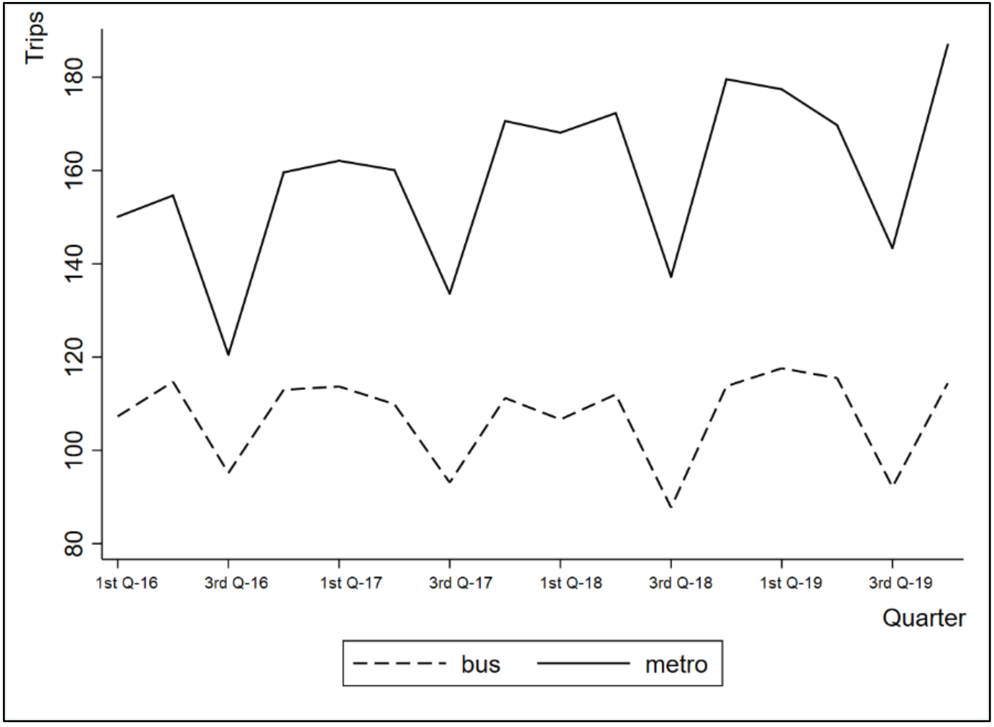
Table 1. Traffic flows by areas (in millions)

	MC LEZ area	Surrounding stations	Other city areas
1st quarter 2016	0.400	2.098	4.059
2nd quarter 2016	0.414	2.168	4.252
3rd quarter 2016	0.393	1.923	3.626
4th quarter 2016	0.394	2.114	4.175
1st quarter 2017	0.405	2.080	4.113
2nd quarter 2017	0.420	2.122	4.164
3rd quarter 2017	0.401	1.859	3.547
4th quarter 2017	0.397	2.058	4.048
1st quarter 2018	0.373	2.030	4.027
2nd quarter 2018	0.371	2.077	4.140
3rd quarter 2018	0.343	1.825	3.497
4th quarter 2018	0.350	2.052	4.042
1st quarter 2019	0.348	1.974	3.923
2nd quarter 2019	0.356	2.049	4.025
3rd quarter 2019	0.340	1.818	3.446
4th quarter2019	0.367	2.059	4.032

Source: Ayuntamiento de Madrid (https://datos.madrid.es)

This decline in traffic might have influenced other modes of transport. Figure 4 displays data on subway (Metro de Madrid) and bus network usages. The use of Metro of Madrid has been following an increasing trend that continued during the MC period, despite some important conservation works that took place in Line 5 (which represents more than 10 percent of the total trips of the underground network) and Gran Via station, which has been closed since August 2018. In any case, the subway network has been expanding in the last years and has a high density of lines and stations in the MC area, that allows travellers to easily connect with the rest of the city and nearby cities and towns. In contrast, in the case of buses, we do not observe a long-term trend beyond seasonal variations. The characteristics of the old Madrid area limit the size of the buses that serves the area and the system cannot be easily expanded.

Figure 4. Metro (subway) and buses trips by quarter (in millions)



Source: Empresa Municipal de Transporte de Madrid

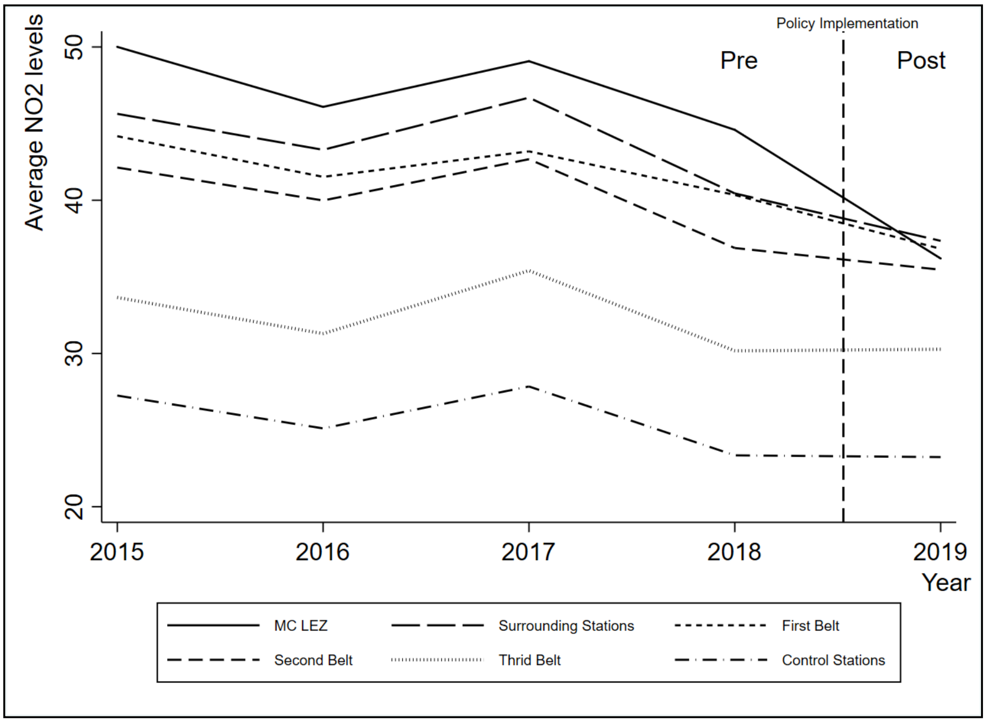
These are mere descriptive data but they suggest that during 2018 and 2019 there was a possible transfer from road traffic to subway network.

5. Diff-in-Diff specification

To evaluate the effectiveness of Madrid Central, we compute the Diff-in-Diff estimates to compare the change in NO_2 levels in Plaza del Carmen within the area of MC (treatment group) relative to the change in NO_2 levels in other areas (control group), following the introduction of the LEZ.

A key identifying assumption of Diff-in-Diff models is the so-called parallel trend assumption, i.e. that the trend in NO_2 emissions for all stations, including the control station, would be the same in the absence of the LEZ implementation. Figure 5 plots the yearly average NO_2 measurements for Plaza del Carmen versus the rest of monitoring stations between January 2015 and May 2019. The vertical line indicates the date of the policy implementation. While there is some year to year variation, inspection of the graph suggests that both treatment and control stations followed a common trend till the application of the LEZ policy, and its implementation led to a deviation of Plaza del Carmen and nearby stations from the common pattern represented by the *second belt*, the *third belt* and the *control stations*. Therefore, potential *spillover* effects concerning *surrounding stations* and the *first belt* should be considered.

Figure 5. NO_2 yearly average measurements



Since the parallel trend assumption seems to be fulfilled, the benchmark model to be estimated can be expressed as follows:

$$NO_{2st} = \alpha + \beta Madrid\ LEZ_s + \gamma POST_t + \delta(Madrid\ LEZ * POST)_{st} + \lambda X_s + MET_{st} + \varepsilon_{st} \qquad (1)$$

where NO_{2st} denotes daily NO_2 concentrations as measured by monitoring station s at time t; Madrid LEZ is a dummy variable that takes value 1 for Plaza del Carmen station; POST is a dummy variable to indicate whether the data corresponds to an observation before or after the implementation of the policy; the coefficient on the interaction between Madrid LEZ and POST, δ, is the Diff-in-Diff estimate of the effect of the introduction of the Madrid Central LEZ on NO_2 measurements. If the normal assumptions regarding Diff-in-Diff estimators are fulfilled, it is interpreted as the effect of the policy on the NO_2 levels in the MC area. Vector X_s includes a set of dummy variables for the type of station: whether background or traffic, urban or suburban.

Additionally, we include meteorological variables that vary over time. Certain weather parameters have been found to be extremely relevant to model air pollutant concentrations, particularly, temperature, wind speed and direction, relative humidity, cloud cover, dew point temperature, sea level pressure, precipitation and mixing layer height (e.g. Dayan and Levy, 2002; Demuzere *et al*., 2009; Russo *et al*., 2014; Zhou *et al*., 2019). For instance, if the air is calm and pollutants cannot disperse, then the concentration of these pollutants will build up. On the contrary, when strong, turbulent winds blow, pollutants disperse quickly, resulting in lower pollutant concentrations (De Nevers, 2000). Despite their relevance to explain pollutant concentrations, just the inclusion of an extensive vector of weather controls does not imply an improvement in the assessment of the potential impact of any policy change. If these variables are time-variant but are constant across stations on each given day, their inclusion would help to increase the proportion of the variance of NO_2 levels explained by the independent variables, but they should be entirely orthogonal to the Diff-in-Diff estimator, leaving $\hat{\delta}$ unaltered. To avoid this irrelevance of covariates problem, we allow meteorological controls to vary across stations by using an inverse gravitational weight based on the distance of each air quality stations to the Madrid nodes of ERA5 gridded dataset[6] (the closest nodes to Madrid are represented in Figure 2).

Accordingly, vector MET_{st} is a set of air station-variant meteorological daily variables that includes daily precipitation, sea level pressure (SLP) and mean relative humidity. Several authors have acknowledged possible non-linear effects between meteorological variables and air pollutant levels. For instance, Borge *et al.* (2019) use smoothing spline functions to model the effect of pressure and precipitation on pollutants, while Roberts–Semple *et al.* (2012) estimate regression models of the natural logarithm of NO_2 on pressure and humidity. Similarly, Kim *et al.* (2014) point that “log-shaped regression equation was most suitable for the expression of pollutant reduction by precipitation amount.” Here, to capture non-linearities, we opt for a quadratic specification of these three variables that allows an additional degree of freedom in the functional form. MET_{st} also includes minimum daily temperature and the daily mean temperature at the 1000 hPa level. Both temperatures allow measuring the vertical daily temperature dispersion (You et al., 2018). Finally, we add the daily main wind component together with the wind intensity. Furthermore, to assess the relevance of these variables, we estimate equation 1 with and without including meteorological conditions.

To account for seasonal effects on air pollution, we include a set of dummies indicating whether a given day is a Saturday, a Sunday or a bank holiday (Pearce et al., 2011). Besides, NO_2 concentrations could be affected by any underlying common trend. For instance, if the use of new more efficient cars, greater environmental awareness or other regulations are cutting down on NO_2 levels, Diff-in-Diff estimated parameters will overestimate the real impact of Madrid LEZ. Alternatively, we can think that if more cars over time circulate within Madrid LEZ, estimated parameters could underestimate the real impact. Therefore, we introduce year-month fixed-effects to capture longer-run trends that may affect air pollution. Finally, ε_{st} is an error term that captures any unobserved factor that may affect NO_2 levels and is assumed to have zero mean, conditional on the monitoring station and time period. Definitions and descriptive statistics of the variables are displayed in Table 2.

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[6] ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. Since 1979, ERA5 data are produced by the European Centre for Medium-Range Weather Forecasts. The meteorological variables used in our analysis were retrieved on an hourly basis for the 2015-2020 period, on a gridded 0.25º x 0.25º spatial resolution, for a selected area encompassing the MC area (Figure 2).

Table 2. Definitions and descriptive statistics

Variable name	Mean	St. Dev.	Definition
NO_2	35.59	20.22	Average daily level of NO2
Madrid LEZ	0.02	0.15	Dummy: 1 if air station at Plaza del Carmen and 0 otherwise
Surrounding Stations	0.10	0.30	Dummy: 1 if air station at Plaza de España, Escuelas Aguirre, Parque del Retiro or Mendez Alvaro and 0 otherwise
First belt	0.12	0.33	Dummy: 1 if air station at Plaza Castilla, Paseo de la Castellana, Barrio del Pilar, Cuatro Caminos or Ramon y Cajal and 0 otherwise
Second belt	0.17	0.38	Dummy: 1 if air station at Arturo Soria, Farolillo, Moratalaz, Vallecas, Plaza Eliptica, Sanchinarro orTres Olivos and 0 otherwise
Third belt	0.17	0.38	Dummy: 1 if air station at Villaverde, Casa de Campo, Barajas, Ensanche de Vallecas, Embajada, El Pardo or Juan Carlos I Avenue and 0 otherwise
POST	0.14	0.35	Dummy: 1 if observation is after the date of implementation of the MLEZ (1st of December 2018) and 0 otherwise
Precipitation	0.05	0.15	Total daily precipitation in inches
Sea Level Pressure	1018.17	7.06	Daily mean sea level pressure in hPa
Relative humidity	57.00	19.49	Daily mean relative humidity in %
Min Temperature	9.00	6.86	Daily minimum temperature in Celsius
Temperature 1000	18.75	7.65	Daily mean temperature at 1000 hPa in Celsius
Northeast wind	0.35	0.98	Northeast wind daily mean speed in m/s
Southeast wind	0.97	1.14	Southeast wind daily mean speed in m/s
Southwest wind	1.03	1.55	Northwest wind daily mean speed in m/s
Northwest wind	0.04	0.35	Southeast wind daily mean speed in m/s
Suburban	0.07	0.26	Dummy: 1 if air station is classified as suburban and 0 otherwise
Sub & background	0.17	0.38	Dummy: 1 if air station is classified as suburban and background and 0 otherwise
Urban & traffic	0.39	0.49	Dummy: 1 if air station is classified as urban and traffic and 0 otherwise
Urban & background	0.32	0.47	Dummy: 1 if air station is classified as urban and background and 0 otherwise
Bank holiday	0.04	0.20	Dummy: 1 if bank holiday and 0 otherwise
Saturday	0.14	0.35	Dummy: 1 if Saturday and 0 otherwise
Sunday	0.14	0.35	Dummy: 1 if Sunday and 0 otherwise

As Clarke (2017) points out, in situations where identification is based on geographic location, the stable unit treatment value assumption (SUTVA) is likely to be violated.

This is because geographical boundaries can be easily crossed, leading to *spillover* effects between treatment and control units. In our context, it is possible that the implementation of the policy has affected not only the objective zone, but may have also generated externalities on other areas, especially those in proximity of Madrid Central. These externalities could be either negative or positive. On the one hand, by restricting polluting vehicle access into the city centre, traffic may have been diverted to other areas, therefore increasing air pollution in nearby zones and inducing a negative *spillover* effect. On the other hand, citizens may have changed their travel behaviour leading to lower air pollution not only in the city centre, but also in other parts of Madrid. This would be a positive *spillover* effect.

To account for these potential *spillover* effects, we estimate different specifications of the model, allowing for multiple "treatment" units. First, we consider the benchmark model where Plaza del Carmen is the only treatment unit. Next, we include a second potential treatment group, the "surrounding stations", which comprises the closest monitoring stations to Plaza del Carmen. In a third specification, we add the three additional "belts", one inside the M30 ring road and two outside. The remaining 21 stations, the ultimate "control" group, are located outside of Madrid city and its municipality and are far enough to be affected by the application of the traffic restrictions in a such diminutive area of the centre of the city. All control units are interacted with the POST variable.

6. Results

In columns (1) and (2) of Table 3, results are displayed assuming Plaza del Carmen as the only treatment unit. In general, coefficients have the expected signs. On average, Plaza del Carmen exhibits higher levels of NO_2 measurements, as indicated by the positive coefficient on the Madrid LEZ variable. Following the implementation of Madrid Central LEZ, there was a significant differential impact of the policy on reducing pollution in Plaza del Carmen area. In particular, after the introduction of the LEZ, NO_2 levels in Plaza del Carmen fell by about 11 µg/m3.

Interestingly, the inclusion of station-variant meteorological controls (column 2) contributes to significantly increase the explanatory capacity of the model, since R-sq increases from around 45% to over 65%, but the estimated effect of the policy remains similar.

Regarding the impact of weather variables, higher levels of relative humidity are associated to lower levels of NO_2, but with a decreasing rate of change. Precipitation also shows a nonlinear effect, positive for low levels and negative for high levels. The positive contribution of precipitation to reduce NO_2 levels may be due to the significant wet cleaning effect of precipitation on atmospheric pollutants (Zhao *et al*., 2019). However, for low levels of precipitation, the higher associated traffic might rise NO_2 concentrations, being precipitation itself not enough to clean the atmosphere.

Similarly, we estimate a non-linear effect for SLP, as in Borge et al. (2019) or Roberts–Semple *et al.* (2012). Given the estimated coefficients and the shape of the curvature, the positive link between SLP and NO_2 is dominant. For pressure levels below 1010 hPa, its effect on NO_2 levels is rather small; however, the expected level of NO_2 increases exponentially as pressure rises above 1013 hPa.

All wind intensity components show a significant negative sign as expected, as they are representative of horizontal dispersion which plays an important role in the modulation and the dissipation of NO_2 concentration (Zhang *et al*., 2015; Zhao *et al*., 2019).

Furthermore, daily minimum temperatures (once temperature at 1000 hPa is controlled) show a significant negative sign. Thus, we estimate a primary negative effect of temperature on NO_2 levels, as Gupta *et al.* (2008), or Wang *et al.* (2020). But as temperature at 1000 hPa increases, so do the expected NO_2 levels.

The daily temperature range, high pressure, low precipitations, and weak winds are associated with stagnation situations. Stagnation is considered to consist of light winds so that horizontal dispersion is at a minimum, a stable lower atmosphere that effectively prevents vertical escape, and no precipitation to wash any pollution away. Therefore, higher stability periods are associated to higher levels of pollutants as in Pearce et al. (2011).

Table 3. Diff-in-Diff models

	(1)	(2)	(3)	(4)	(5)	(6)
	MODEL1	MODEL2	MODEL3	MODEL4	MODEL5	MODEL6
Madrid LEZ	9.672***	9.467***	10.56***	10.39***	22.49***	22.71***
(Plaza del Carmen)	(8.26)	(7.85)	(7.48)	(7.15)	(5.44)	(4.91)
Surrounding Stations			5.409	5.656	13.61***	14.18***
(PE, EA, RE, MA)			(1.23)	(1.25)	(3.28)	(3.14)
First belt					6.144**	6.495**
(inside M30)					(2.54)	(2.23)
Second belt					12.44***	12.88***
(just outside M30)					(2.91)	(2.74)
Third belt					16.14***	16.62***
(even further but within Madrid city)					(3.69)	(3.41)
POST	-14.90***	-20.17***	-14.72***	-19.92***	-14.60***	-19.12***
	(-17.95)	(-19.06)	(-17.61)	(-19.49)	(-14.58)	(-18.21)
Madrid LEZ* POST	-10.91***	-10.96***	-11.09***	-11.15***	-11.19***	-11.42***
	(-26.71)	(-26.63)	(-25.32)	(-25.25)	(-14.91)	(-15.32)
Surrounding Stations* POST			-1.764**	-1.836**	-1.878*	-2.127**
			(-2.20)	(-2.36)	(-1.87)	(-2.17)
First belt * POST					-0.573	-0.983
					(-0.68)	(-1.19)
Second belt * POST					-0.557	-0.842
					(-0.45)	(-0.67)
Third belt * POST					0.361	0.0818
					(0.35)	(0.08)
Relative humidity in %		-0.0162		-0.0136		0.00391
		(-0.27)		(-0.24)		(0.08)
Relative humidity in % Squared		-0.000475		-0.000467		-0.000390
		(-1.15)		(-1.15)		(-1.00)
Precipitation in inches		17.89***		18.03***		18.58***
		(8.00)		(8.25)		(9.68)
Precipitation in inches Squared		-8.894***		-9.028***		-9.706***
		(-4.92)		(-5.17)		(-6.99)
Sea Level Pressure in hPa		-33.14***		-32.87***		-31.12***
		(-9.26)		(-9.47)		(-10.52)
Sea Level Pressure in hPa Squared		0.0163***		0.0162***		0.0154***
		(9.29)		(9.50)		(10.54)
Min Temperature in Celsius		-1.733***		-1.756***		-1.889***
		(-5.83)		(-6.19)		(-9.16)
Temperature at 1000 hpa in Celsius		1.860***		1.880***		2.004***
		(6.43)		(6.75)		(9.34)
Northeast wind in m/s		-6.603***		-6.575***		-6.384***
		(-16.78)		(-17.20)		(-20.12)
Southeast wind in m/s		-5.966***		-5.939***		-5.706***
		(-12.83)		(-13.11)		(-15.68)
Southwest wind in m/s		-5.481***		-5.459***		-5.293***
		(-16.79)		(-17.14)		(-19.52)
Northwest wind in m/s		-6.700***		-6.637***		-6.258***
		(-14.88)		(-15.26)		(-15.46)
Sub & background	-3.085	-4.077	-3.085	-4.082	-3.085	-4.110
	(-0.66)	(-0.89)	(-0.66)	(-0.89)	(-0.66)	(-0.89)
Suburban	-6.365	-8.421*	-6.365	-8.425*	-22.56***	-25.07***
	(-1.43)	(-1.90)	(-1.43)	(-1.90)	(-3.61)	(-3.79)
Urban & traffic	13.08***	11.00**	12.43***	10.31**	7.966*	5.619
	(2.89)	(2.43)	(2.79)	(2.31)	(1.74)	(1.17)
Urban & background	9.842**	8.286*	8.982**	7.386*	-2.933	-4.895
	(2.36)	(2.02)	(2.12)	(1.76)	(-0.51)	(-0.80)
Bank holiday	-7.175***	-11.10***	-7.174***	-11.11***	-7.179***	-11.18***
	(-19.87)	(-21.20)	(-19.87)	(-21.30)	(-19.81)	(-21.85)
Saturday	-7.213***	-6.697***	-7.213***	-6.699***	-7.212***	-6.716***
	(-23.47)	(-22.47)	(-23.48)	(-22.50)	(-23.48)	(-22.74)
Sunday	-11.93***	-10.77***	-11.93***	-10.77***	-11.93***	-10.78***
	(-26.40)	(-25.67)	(-26.41)	(-25.66)	(-26.43)	(-25.65)
Constant	31.32***	16,828***	31.29***	16,689***	31.25***	15,793***
	(7.71)	(9.22)	(7.70)	(9.43)	(7.73)	(10.50)
Year-month fixed-effects	YES	YES	YES	YES	YES	YES
Observations	52,124	52,124	52,124	52,124	52,124	52,124
R-squared	0.445	0.657	0.451	0.663	0.484	0.698
R-squared adj.	0.445	0.657	0.450	0.663	0.483	0.697

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Reference category: Urban or suburban air stations outside Madrid municipality but within the Autonomous Community of Madrid.

Not surprisingly, NO_2 levels are lower during the weekend days or bank holidays, especially during Sundays. Finally, measured NO_2 emission levels are higher in urban stations (and specially in traffic stations) and lower in suburban stations relative to industrial monitoring stations, the reference category.

Columns (3) and (4) of Table 3 report the results of adding a second treatment group, the four stations that are closest to Plaza del Carmen, with and without meteorological controls, respectively. As it can be seen, average NO_2 measurements in nearby stations fell significantly, around 1.8 µg/m3, following the introduction of Madrid LEZ but, as expected, by a much lower amount than in Plaza del Carmen. Moreover, the inclusion of this additional treatment unit leaves the estimated coefficients for Plaza del Carmen almost unchanged. Hence, traffic diversions through the nearby areas to avoid crossing the MC LEZ do not seem to be very common. In fact, no increasing level of NO_2 is observed in the surrounding air quality stations; on the contrary, small and significant NO_2 drops are perceived, that may be evidence in favour of new transportation habits.

Finally, columns (5) and (6) display estimations considering a wider range of treatment units, located further and further from the LEZ. Coefficients of the interactions between POST and *First Belt*, *Second Belt* and *Third Belt* dummy variables are not significantly different from zero, implying that the implementation of the policy had no significant impact on stations as we move further away from the LEZ, at least comparing their changes in the NO_2 levels with those in the monitoring stations located far away from Madrid city centre. The coefficients on Plaza del Carmen and Surrounding stations are roughly the same as in the previous specification. In all cases, including meteorological controls significantly contributes to increase the explanatory capacity of the model, as measured by the R-square, but has not impact on the estimations of policy impact on NO_2 values.

While identification in this analysis relies on the parallel trend assumption, a related issue that may prevent us from assuming causality is the potential existence of heterogeneous space-time effects due to shocks or policies other than the LEZ implementation. For instance, an increase in the petrol price may likely have its most substantial effects in central Madrid, where better public transit and higher densities make walking, biking, and public transport relatively more attractive, decreasing traffic relatively more than in other areas. We can rule out this specific factor since, compared to the period previous to its implementation, the price of petrol did not change much while the MC LEZ was in operation (according to figures from the Weekly Oil Bulletin of the European Commission).

Furthermore, we might expect a recession to have uneven spatial effects with driving (and thus local pollution) decreasing the most in parts of the city where it is easier to replace car rides with trips by other modes. However, this was not the case, since Madrid GDP increased, on average, more than 4 percent annually from 2015 to 2019. Since average income is higher in central Madrid than in the rest of the province, we might expect an especially large income-effect on transport services throughout the period in this area. Ceteribus paribus, this could have resulted in higher levels of pollutants associated with traffic. This being the case, Diff-in-Diff models would underestimate the real effect of the implementation of MC LEZ.

Another alternative explanation to the NO_2 reduction in central Madrid that could threaten the causal validity of the findings, could be the heterogeneous impact on the cost of driving due to public works undertaken during the period of study. As mentioned above, Gran Via, the main avenue crossing the LEZ, was completely renovated. However, these works took place just before the implementation of the LEZ (April 2018 to November 2018). We have estimated again the model including a dummy variable for public works within the MC area, interacted with the different areas considered. We found that, although public works were associated with significant city-wide traffic drops, there were not significantly different effects between areas and, therefore, the main results were not affected.

Therefore, our findings provide evidence that the introduction of Madrid LEZ has had a positive impact on reducing NO_2 emissions, as measured by Plaza del Carmen. Additionally, these results are consistent with the existence of positive *spillover* effects, whereby adjacent stations to the LEZ experienced significant reductions in NO_2 emissions following the implementation of the policy, but of a lower magnitude.

7. Conclusions and Policy Implications

Due to the growing concern regarding air pollution and the costs it imposes on the economy and people’s health, policies designed to reduce air pollution are becoming more common. Many urban cities are trying to diminish the impacts on air quality reducing traffic levels and implementing low-emission zones (LEZ) with different levels of constraints on pollutant vehicles. In this regard, Madrid Central LEZ is an ambitious plan since prohibited vehicles cannot access the area, not even paying an entrance fee. In this paper, we analyse the impact of this policy on NO_2 emissions in the urban area of Madrid. The proposed approach, which is based on Diff-in-Diff model, is appropriate to analyse changes in air quality associated with the implementation of new policies. Therefore, it can also be useful to support the decision-making process related with the maintenance or redraw of the current and future LEZs.

Once meteorological conditions and time effects are controlled for, we estimate a reduction of NO_2 levels between 23-34% in Plaza del Carmen with respect to its pre-policy levels. This means that the annual NO_2 concentration level measured in the only monitoring station within the LEZ (a background station) dropped well below the annual EU established threshold of 40 $\mu g/m^3$; a threshold that had never been attained since this monitoring station registers air quality. This result is in accordance with those related to NOx in London (Ellison et al., 2013; Carslaw *et al.* 2016); Amsterdam (Panteliadis *et al.*, 2014) or Berlin (Lutz, 2009; Jiang *et al.*, 2017).

We also show that there are not negative effects on any of the other monitoring stations outside the LEZ. In fact, in four nearby air quality stations outside the MC LEZ, we find significant reductions in NO_2 levels of about 1.8 $\mu g/m^3$ following the implementation of the policy. As expected, these drops are lower than those estimated for Plaza del Carmen, but still considerable. This evidence on a positive externality due to the establishment of the Madrid LEZ can be understood as if, instead of traffic diversions increasing NO_2 concentrations in other areas, MC LEZ may have encouraged changes in transportation habits, reducing the use of private cars and increasing the use of the public transport network, especially the underground.

In conclusion, these results highlight the validity of the LEZ initiatives in the reduction of pollutants' concentration in big cities. Moreover, although the effects on pollutant levels in areas where a LEZ is established are quite robust, there is less evidence regarding potential uneven spatial effects associated to such policies. This study, therefore, contributes to reducing uncertainty in the existing literature on possible *spillover* effects. Additionally, since the effects of meteorological parameters on concentrations often mask subtler effects of a LEZ (Holman et al., 2015), a study like the one we present, which separates the influence of different types of variables, poses as an advantage.

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