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Is vehicle scrapping affected by low-emission zones? The case of Madrid

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ABSTRACT

This paper provides an initial empirical evaluation of the possible impact a low-emission zone (LEZ) has on vehicle scrappage rates. The analysis is based on a quasi-experimental design, which is applied to the Spanish case known as *Madrid Central*. Our results, which are quite robust to reasonable changes in the geographic areas used as controls, reveal an excess of scrapping decisions by vehicle owners in the city of Madrid following the implementation of this urban policy. This excess scrapping is transitory and particularly notable for old vehicles subject to major traffic restrictions. The results suggest that establishing a LEZ in a relatively small area can generate some social gains, in terms of transport safety and removal of the vehicles that pollute the most, which may outweigh the simple benefit of improving air quality in the area.

1. Introduction

It is widely recognized that a vehicle becomes less roadworthy as it gets older. The increase of accident risk with each additional year of vehicle age is quite remarkable, about 7.8% according to estimates by Keall and Newstead (2013), compromising road safety as a result. Moreover, a large body of research shows that internal combustion vehicles with older technologies can emit higher levels of dangerous fumes, thus exposing people to high air pollution (Harrington, 1997; Zachariadis et al., 2001; Beydoun and Guldmann, 2006; Chen and Borken-Kleefeld, 2016; Pandey et al., 2016; Grigoratos et al., 2019; Bernard et al., 2020; Smit et al., 2021). This effect contributes significantly to the recognition of the road transport sector as responsible for most of the concentration of nitrogen oxides (NO_x) and also largely responsible for breathable particulate matter ($PM_{2.5}$ and PM_{10}) detected in urban areas (e.g., Grice et al., 2009; Wang et al., 2010; Font et al., 2019). High values of either air pollutant, particularly in cities that regularly exceed the emission limits recommended by the World Health Organization (WHO) (Sicard et al., 2021), are the cause of many respiratory, cardiovascular, and malignant diseases (e.g., Künzli et al., 2000; Landrigan, 2017; Shima, 2017). Estimations of the social and economic damage in terms of individual health expenditure, public medical costs, and life-years lost (e.g., Deryugina et al., 2019; Chen and Chen, 2021) suggest that policies aimed at reducing emissions from road transport deserve urgent attention.

One urban policy intervention widely used to deal with this environmental problem is to create low-emission zones (LEZs). These initiatives aim to enhance air quality by restricting the circulation of the most polluting vehicles in a specific area within the city. In turn, other interventions promoting the scrapping of older vehicles with polluting technologies may lead to air quality improvements in any of the geographical areas in which these vehicles previously circulated. Moreover, simply eliminating older vehicles is likely to have some additional benefits, such as a relative increase in the technical efficiency and the transportation safety of the national fleet which, in turn, will probably be strengthened by the gradual replacement with new vehicles. Both policy interventions – LEZs

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and vehicle scrapping campaigns – have been intensively debated, although essentially independently of one other. In this paper we ask to what extent establishing a LEZ could also be considered as a tool to accelerate the scrapping of vehicles with older technologies, thus having beneficial effects beyond simply improving air quality within the area where circulation is restricted.

To empirically address this question, we will focus on the first LEZ in Spain, known as *Madrid Central*. The creation of a LEZ at the end of 2018 was particularly urgent in the case of Madrid because it was quite evident that the poor air quality in the city was generating serious problems in the health of the resident population (Khomenko et al., 2021). There is little doubt that this situation is largely associated with the older internal combustion vehicles in circulation. This can be seen, for example, from the continuous monitoring carried out (by OPUS Remote Sensing Europe)[1] on the real traffic in the city of Madrid from November 2018 to April 2020. More than 450,000 vehicles, mainly passenger cars (83.4%) and vans (12.2%), were analyzed, including those the Spanish traffic authority classifies as potentially highly polluting, i.e., categories A and B. These two categories cover gasoline powered cars and light commercial vehicles registered before January 2006, and those powered by diesel registered before September 2015. These vehicle types represent 57% of all vehicles in circulation, but estimates show that they are responsible for about 84% of NO_x and 93% of particulate matter emissions generated by the light vehicles circulating in the city.

The question we will explore in this research seems to us of special interest for at least two reasons. First, it attempts to fill a gap in a wide and interesting stream of literature on potential policy interventions to accelerate scrapping; and second, it is a timely question from a practical point of view. In fact, LEZs are increasingly being promoted in the EU and, particularly, in Spain. The European Parliament considers such interventions to be one of the best practices for improving air quality in cities (Nagl et al., 2018). In turn, Spain's Climate Change and Energy Transition Law (Law 7/2021) has recently embodied an extraordinary commitment to expanding LEZs across the country. Specifically, the law states that all cities with more than 50,000 inhabitants must have a LEZ before 2023. This condition will also be applicable to municipalities with more than 20,000 inhabitants when they exceed the maximum values of airborne pollutants (regulated in Royal Decree 102/2011).[2]

The remaining sections of this paper are organized as follows. In Section 2 we present an overview of the literature on the main automobile scrappage policies as well as research shedding light on the environmental performance associated with LEZs. Section 3 describes the case of the LEZ in Madrid. The research design, our data, the econometric specification, and the corresponding results are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. Background

2.1. Vehicle scrappage

Air quality gains are the most direct and appealing social benefits attributed to decisions to scrap old vehicles. However, because the scrapped vehicle is usually replaced by a new one, it could also benefit the automotive industry with a carryover effect on other sectors. It is reasonable to expect that the resulting composition of the automobile fleet will, in turn, lead to fuel savings and improvements in transport safety. Unsurprisingly therefore, encouraged by these arguments, many regional and national governments have been directly or indirectly involved in the application of programs aimed to accelerate the retirement of old vehicles.

A growing interest in implementing these programs stems from the USA Clean Air Act Amendments, which in 1990 included the possibility that they could be financed by private companies subject to emission limits (ECMT, 2000). In exchange, these companies would obtain emission reduction credits or advantages in the legal emission requirements. The oil company *Unocal Corporation* implemented the first scrapping program in Southern California in the same year, followed by similar program roll-outs by other companies in other areas of the USA such as Chicago and Delaware in 1992. The initial retirement schemes in Europe were directly financed by individual governments. The nationwide cases of Greece in 1991, and Denmark, France, and Spain in 1994, were the beginning of an intervention that has been carried out repeatedly since then. The degree of success of these programs obviously depends on the context in which they are implemented, but it is also affected by program design aspects such as the minimum age of the vehicles included in the scheme, whether or not owners are obliged to buy a less polluting vehicle (cash-for-replacement versus cash-for-scrappage), or the amount of compensation owners receive (through scrappage rebates or subsidies).

Policy evaluation in this area of research is not a straightforward task and the indiscriminate use of accelerated vehicle retirement programs was soon questioned by Hsu and Sperling (1994) and Beaton et al. (1995). According to these authors, researchers must first solve the difficult question of how much earlier old vehicles are retired than they otherwise would have been with no intervention strategy, a question that had not been rigorously solved by the reports published up to then. Subsequently, a generation of studies attempted to disentangle the impact of vehicle retirement stimulus through survey responses from vehicle owners (e.g Alberini et al., 1995, 1996; Kavalec and Setiawan, 1997; Dill, 2004), followed by another stream of recent investigations applying econometric techniques to large databases of objective information to control regular scrapping patterns (e.g Sandler, 2012; Laborda and Moral, 2019).

The literature presents evidence that certain programs have had beneficial effects in terms of closely related goals such as increasing scrappage rates for the oldest vehicles, reducing the average age of the car fleet, or lowering certain pollutant

[1] This company's laboratory (ISO-17025) is accredited for the remote measurement of real-world traffic emissions. The results discussed here can be found in the company report at OPUS (2020).

[2] A recent regulation (Royal Decree 1052/2022) currently establishes the minimum requirements that LEZs must meet in terms of air quality, climate change, development of modes of transport, energy efficiency, and noise.

emissions (e.g. Alberini et al., 1996; Baltas and Xepapadeas, 1999; Yamamoto et al., 2004; Cantos-Sánchez et al., 2018; Laborda and Moral, 2019). For instance, the recent paper by Laborda and Moral (2019) analyzing the impact of a series of "cash for clunkers" programs run in Spain from 2011 to 2017 indicates that, regardless of the stage of the business cycle, they were a useful tool to reduce the average age of the automobile fleet. This is not only because older car owners are the beneficiaries of the programs, but also because, according to Cantos-Sánchez et al. (2018), the probability of buying a new car by these owners is increased. However, not all conclusions about the programs' effectiveness have been optimistic. The review of research on this topic by Van Wee et al. (2011) clearly shows that in environmental terms, many studies find the effectiveness of scrapping schemes to be rather modest. Exceptions occur in some programs run in large, densely populated areas and limited to cars with old (or no) emissions control technologies. However, according to Brand et al. (2013), programs in the USA and Europe have usually been used indiscriminately because they are essentially motivated by the desire to stimulate the car market. Even if we accept that this could be the main purpose, it does not seem to be sufficiently justified by the evidence. The impact programs have in accelerating scrapping is essentially found to be transitory (Van Wee et al., 2011), while creating the basis for subsequent activity in the automotive sector turns out to be relatively low (Adda and Cooper, 2000). When the costs associated with the incentives (usually paid in full by governments) are also taken into consideration (i.e., cost-effectiveness analysis) or, alternatively, in a more complex analyses that attempt to measure both the social costs and benefits (i.e., cost–benefit analysis), it is obvious that most retirement programs have little to recommend them (Van Wee et al., 2011).

According to the paper by Sandler (2012), in the future these programs, which are highly subject to adverse selection, should be replaced by other policy alternatives. This is because the limited effectiveness of the programs will tend to be further reduced over time, once the automobile fleet incorporates improved technology. Fortunately, other studies report that vehicle retirement programs are not the only tool to encourage consumers to scrap their older vehicles. Policy interventions involving purchase taxes and feebates on the purchase of efficient vehicles are shown to be useful and have more effective impacts on emissions than the retirement schemes (Brand et al., 2013). Another widely analyzed policy intervention concerns taxes on gasoline and diesel consumption. Research has revealed that an increase in fuel taxes encourages shifts in demand from used to new vehicles and accelerates scrappage, which has a favorable effect on the fuel economy of the vehicle fleet (Li et al., 2009; Jacobsen and Van Benthem, 2015; Bento et al., 2018).

2.2. Environmental effects of LEZs

A comprehensive body of research on the environmental effects of LEZs based mainly on information from monitoring stations provides some important information. The studies carried out for the LEZs in large cities such as Berlin Cyrys et al. (2014), Rome (Cesaroni et al., 2012), London (Ellison et al., 2013), Amsterdam (Panteliadis et al., 2014), Lisbon (Ferreira et al., 2015; Santos et al., 2019), and Madrid (Salas et al., 2021) are good examples. Despite the heterogeneity of results due to differences in local restrictions and types of vehicles regulated (Ezeah et al., 2015; Holman et al., 2015), most of the available studies find that these interventions lead to an improvement of the air quality in the LEZ.

There is also a lively debate on whether creating a LEZ really has a beneficial effect as a whole or, on the contrary, it implies some displacement of the polluting traffic to areas outside the zone. To gain a broader view of the effects of LEZs, a few studies have further analyzed possible spillover impacts on the surrounding areas. On the one hand, one hypothesis is that traffic restrictions could prompt drivers of polluting vehicles to take alternative routes around the LEZ, thus traveling greater distances. On the other hand, the compulsory use of cleaner transportation inside a LEZ may also improve the mobility habits of citizens outside the area. Recent evidence indicates that both these hypotheses are feasible. For instance, some negative spillover effects have been suggested by Lurkin et al. (2021) and Zhai and Wolff (2021) for the London case. The first of these studies finds an increase in traffic on the surrounding roads, while the results from the second paper indicate that the negative spillover effect was only significant for the first five months after the LEZ was put in place. The recent paper by Salas et al. (2021) based on measurements of nitrogen dioxide emissions levels offers especially interesting results for our case, namely, that the monitoring stations located in the surroundings of the Madrid LEZ also find a significant decrease in emissions.

In this debate in pursuit of more effective policies to improve air quality in cities, some aspects remain to be clarified. Perhaps one of the most interesting questions is the impact of LEZs on the scrapping rates of the most polluting vehicles. At the moment, the research suggests LEZs have direct benefits on the quality of the air within their areas. However, to the best of our knowledge, we still have no evidence of whether this particular strategy, which is becoming more and more urgent to improve air quality in congested areas, may also generate incentives to scrap older vehicles.

3. LEZs and the case study

Since the first low-emission zones (LEZs) were implemented in some Swedish cities (Stockholm, Gothenburg, and Malmö) in 1996, this urban access regulation has gradually spread to other European countries, to the extent that there were more than 250 LEZs in the EU by the end of 2019 (Müller and Petit, 2019). Their introduction in Spain has been limited and fairly recent, with only one LEZ established by that date. The case in question is the relatively small (472 hectares) area in Madrid known as *Madrid Central*. Reducing emissions in the most populated and congested city in Spain was conceived as especially urgent and pertinent, since congestion, largely generated by high personal vehicle mobility from the suburbs (Picornell et al., 2019), had been causing significant concentrations of pollutants deemed harmful for health. Indeed, road traffic generated up to 90% of Madrid's nitrogen dioxide emissions (NO_2) (Borge et al., 2014). In response, from mid-July to mid-November 2018, traffic signs were installed that would delimit the LEZ, and the city council launched a public information campaign on billboards and through the mass media. We might reasonably expect such policy interventions to generate some concern in the affected population and interest in finding out details of the restrictions. Indeed, data from Google Trends (https://trends.google.es/) shows a gradual but very slight increase in searches for *Madrid Central* during October of that year, followed by a spectacular rise in the number of searches in the two weeks before the regulation came into force on November 30, 2018.[3]

The traffic regulation in *Madrid Central*, as well as the further restrictions and subsequent expansion of this LEZ, relies on the Spanish classification of vehicles according to their pollution potential (Royal Decree 2822/1998). Vehicles powered exclusively by internal combustion engines were affected by the regulation, with some exceptions, such as vehicles already owned by residents of the *Madrid Central* area. General access to the LEZ was prohibited for vehicles without an environmental label (category A classification), including passenger cars and light commercial vehicles with gasoline and diesel combustion engines registered before 2001 and 2006, respectively. Moreover, in general terms, those vehicles with the most modern combustion engines (classified in both categories B and C) were only allowed to park in private and public designated areas. Following a change in the local government in mid-2019, public announcements suggested some traffic regulations would be relaxed, but as a whole, the above mentioned measures remained unaltered during 2019. Some specific restrictions started in early 2020 and, after the State of Alarm decreed by the Spanish Government in March of that year due to COVID-19, an extraordinary period began in which all citizens' movements were restricted. Finally, it is worth mentioning the recent renewed interest in creating new traffic restrictions in the city (reflected in the Sustainable Mobility Ordinance of September 13, 2021). This new plan, called *Madrid 360*, essentially consists of the continuous expansion of the current restrictions to further districts, culminating with the declaration of a LEZ for the entire city in 2025.

4. Empirical analysis

4.1. Research design and data

With the aim of evaluating the impact of this urban policy intervention, we focus on the number of scrapped vehicles in locations surrounding the Madrid LEZ. Specifically, we examine scrappings in 58 postal code districts surrounding the LEZ within the municipality of Madrid. It seems reasonable to expect that the owners of vehicles in these locations will be particularly affected by the *Madrid Central* traffic restrictions. Our control group consists of postal code districts of large cities, which are expected to be more comparable to Madrid than other Spanish locations, at least in terms of socio-demographic features. Specifically, we selected the 121 postal code districts in municipalities with more than 500,000 inhabitants (i.e, Barcelona, Málaga, Sevilla, Valencia and Zaragoza). We also created a wider alternative control group of scrappings in the 247 postal code districts belonging to the municipalities with more than 250,000 inhabitants (i.e., Alicante, Barcelona, Bilbao, Córdoba, Gijón, Hospitalet de Llobregat, Málaga, Murcia, Sevilla, Valencia, Valladolid, Vigo, Vitoria and Zaragoza). Interestingly, we can expect the share of the type of vehicles affected by traffic restrictions due to the LEZ in Madrid to be quite similar to that of the control groups. For instance, according to data from December 2017 provided by the Spanish Directorate-General for Traffic, the share of these vehicles (i.e., those without an environmental label and those classified in categories B and C) was 83.3% in the municipality of Madrid, and 86.8% (85.5%), on average, in the municipalities with more than 250,000 (500,000) inhabitants.

Fig. 1 shows a map of the Spanish mainland, highlighting the postal code districts belonging to the LEZ, and the surrounding area within the municipality of Madrid, where it is assumed that a proportion of the registered vehicles could potentially be affected. The map also displays the location of the cities comprising the control groups for scrapping purposes. Because these locations are relatively far from *Madrid Central*, it is reasonable to think that their residents will probably be hardly affected, if at all, by its traffic restrictions.[4] In any case, it should be taken into account that the vehicle owners in these remote cities might also be tempted to scrap some vehicles due the Madrid LEZ. That is, the implementation of this urban measure in Madrid could reinforce the expectation of a new LEZ also being introduced in the near future in the vehicle owner's city, giving rise to an additional number of scrappings even though the locations are far apart. In turn, in line with the empirical results from (Börjesson et al., 2021),[5] it is conceivable that there could be a general decrease in the prices of those used vehicles to which the implemented urban measure is addressed. This would imply a reduction in the opportunity cost of removing this sort of vehicles anywhere in the country. Thus, it should be considered that the empirical results we will provide could be underestimating, to a certain extent, the existence of a hypothetical number of vehicles scrapped exceptionally as a consequence of the traffic restrictions applied in *Madrid Central*. In this sense, the subsequent results should be interpreted strictly as relative to the control groups.

Our data were taken from the Spanish Directorate-General for Traffic. This office provides regular information on all registered vehicles that are definitively withdrawn from circulation in Spain, detailing the date and place of withdrawal. For our purposes, we assembled a panel data set of the quarterly amount of scrapped passenger cars and vans by each postal code considered. The time period runs from December 2017 to November 2019, that is, four quarters after the LEZ was implemented but also four quarters

[3] Madrid city council approved this regulation on October 5, 2018 and the decision was published in the Official Bulletin of the Community of Madrid on October 23, 2018).

[4] The city in the control group that is closest to *Madrid Central* is Zaragoza, which is 322 kilometers away, when only the cities with more than 500,000 inhabitants are considered. When cities with more than 250,000 inhabitants are considered, the closest city in the control group is Valladolid, which is 210 kilometers away.

[5] This paper shows that the prices for the specific cars that would be banned in a LEZ planned in Stockholm plummeted at the national market level, apparently as a consequence of the introduction of this LEZ being announced in the media.

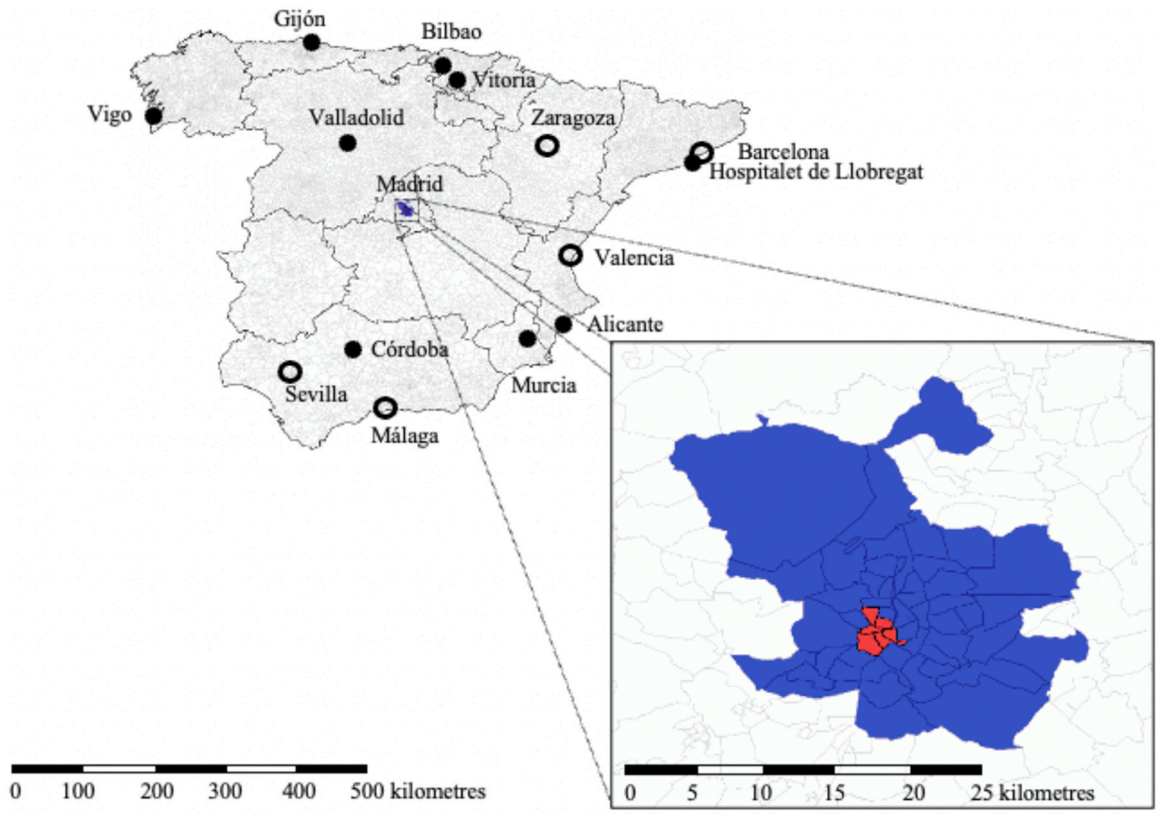

Fig. 1. Madrid city, their LEZ, and control municipalities. The postal codes belonging to the LEZ are highlighted in red, while the blue area corresponds to the surrounding postal code districts within the municipality of Madrid. Filled circles indicate the location of municipalities with more than 500,000 inhabitants, while empty circles represent municipalities with population between 250,000 and 500,000 inhabitants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

before. Then, the examination of this period will allow us to analyze how the implementation of the LEZ (or its announcement) could affect scrapping. A preliminary analysis of the resulting data set reveals that 99.9% of the scrapped vehicles were fairly polluting, since they had type A or B classifications. In Table 1 we also present the average number of vehicles scrapped (and the corresponding standard errors) in the postal code districts belonging to the treatment and control groups, over the quarters considered.[6] As can be seen, both the mean and the dispersion measure are higher in the postal code districts surrounding the LEZ within the municipality of Madrid than in the remaining postal code districts. This fact is probably related to the size differences in the vehicle fleet. A slight, one-off increase in the immediately post-policy period can also be seen, which seems particularly relevant in the case of Madrid. In the next section we carry out two analyses to find out the extent to which the observed evolution of scrapped vehicles in Madrid could be attributed to the LEZ scheme.

4.2. Baseline specification and results

To assess the effectiveness of the urban policy intervention, we employ the following event study model:

$$s_{it} = \sum_{\tau=-4}^{3} \beta_\tau Z_i D_{t_0+\tau} + \alpha_i + \lambda_t + \epsilon_{it} \tag{1}$$

where s_{it} refers to the number of scrapped vehicles in postal code district $i = 1, 2, \ldots, N$ and quarter $t = 1, 2, \ldots, T$, Z_{it} is a dummy variable that equals one when postal code district i belongs to the area surrounding the LEZ, and D_t is a dummy variable that equals one in observations corresponding to the different quarters (τ) before and after the LEZ was introduced in t_0. Our specification also includes individual (α_i) and time (λ_t) fixed effects. The former helps us to control for unobserved time-invariant heterogeneity, which may reflect, among other factors associated with each postal code district, differences in distance between each location to the LEZ and discrepancies in the size of the automobile fleet. The latter captures variations in vehicle scrapping common to all locations in

[6] Data to replicate our results are available at https://www.doi.org/10.17632/f38zrhc2k7.1.

Table 1
Scrapped vehicles by quarter and geographical area.

	Madrid	Other municipalities with more than:	
		500,000 inhabitants	250,000 inhabitants
Dec 2017–Feb 2018	159.8 (12.4)	79.0 (4.5)	67.0 (2.8)
Mar 2018–May 2018	150.6 (11.7)	75.2 (4.6)	62.9 (2.8)
Jun 2018–Aug 2018	159.8 (12.5)	83.1 (5.1)	67.8 (3.1)
Sep 2018–Nov 2018	156.9 (12.0)	84.5 (5.1)	70.4 (3.1)
Dec 2018–Feb 2019	178.9 (14.1)	88.8 (5.2)	74.1 (3.2)
Mar 2019–May 2019	163.6 (13.0)	79.6 (4.7)	68.7 (3.0)
Jun 2019–Aug 2019	155.1 (11.7)	79.6 (4.6)	65.8 (2.8)
Sep 2019–Nov 2019	144.1 (11.1)	85.8 (5.0)	70.4 (3.1)

Average number of scrapped vehicles in each postal code. Standard errors in parentheses. There are 58 postal codes surrounding the LEZ within the municipality of Madrid, while municipalities with more than 500,000 (250,000) inhabitants are divided in 121 (247) postal codes.

Table 2
Estimated results from Eq. (1) with the baseline design.

	Pop. over 500,000	Pop. over 250,000
β_{-4}	4.41 (5.32)	3.01 (5.27)
β_{-3}	−0.91 (2.64)	−1.98 (2.58)
β_{-2}	0.44 (2.71)	2.28 (2.63)
β_{-1}	−3.94 (2.44)	−3.31 (2.38)
β_0	13.78 (3.90)***	15.03 (3.82)***
β_1	7.66 (2.97)**	5.18 (2.95)*
β_2	−0.85 (2.92)	−0.51 (2.82)
β_3	−17.97 (2.79)***	−16.07 (2.67)***
Obs.	1432	2440
N	179	305
T	8	8

Regressions include postal code and time fixed effects. Parameters before the policy intervention are normalized according to Eq. (2). Clustered standard errors at postal-code level are presented in parenthesis.
*Denote statistical significance at the 10% level.
**Denote statistical significance at the 5% level.
***Denote statistical significance at the 1% level.

a given time period, which may result, for example, from fuel price changes or some technological improvements. Finally, ϵ_{it} is the error term.

The parameters β_τ measure the quarterly average excess of vehicle scrappings in the postal code districts belonging to the traffic influence area surrounding the LEZ, relative to the postal code districts belonging to other comparable municipalities, in accordance with the proposed research design. Thus, the parameters β_τ for $\tau = -4, -3, -2$ and -1 capture possible effects in the four quarters prior to the introduction of *Madrid Central*, while β_τ for $\tau = 0$, 1, 2 and 3 measure possible effects in the four quarters after the LEZ came into effect. To avoid perfect collinearity, we chose to normalize the parameters β_τ with respect to the corresponding average excess of scrappings before the LEZ was implemented:

$$\sum_{-4}^{-1} \beta_\tau = 0 \tag{2}$$

Table 2 reports the Ordinary Least Squares (OLS) estimates of Eq. (1) with the normalization given in Eq. (2), considering the municipalities with more than 500,000 and 250,000 inhabitants. Additionally,

Table 3 presents some test results for certain null hypotheses that may be especially interesting for our purpose. As can be seen, the results are fairly similar regardless of the population threshold considered. All the estimated coefficients are jointly relevant, but those corresponding to the quarters before the LEZ are statistically not significant, neither individually nor jointly. This suggests that during the quarters before the scheme began, vehicle scrapping in the postal code districts within the municipality surrounding the LEZ was statistically indistinguishable from scrapping in the postal code districts of the other cities. That is, the results indicate that there are no effects caused by the announcement of the urban measure.

From the individual estimated coefficients we further obtain a significant excess of scrapped vehicles during the first two quarters after the LEZ was implemented (i.e., from December 2018 to May 2019) in relation to the control locations. We can calculate the excess in percentage terms over the average number of scrapped vehicles in these quarters (displayed in Table 1). Namely, if we take into account our estimated coefficients when we control for the cities of more than 500,000 inhabitants, it suggests that there is a relative increase in scrappage of about 7.71% and 4.68% in the first and second quarter immediately after the creation of LEZ, respectively. Alternatively, if we consider the results obtained when we control for the cities with more than 250,000 inhabitants, the estimated increase in scrapping is quite similar. Specifically, relative scrapping levels rise by about 8.42% and 3.17% in the first

Table 3
Joint significance test.

H_0	d.f.	Pop. over 500,000		Pop. over 250,000	
		χ^2	*p*-value	χ^2	*p*-value
(a) $\beta_{-3} = \beta_{-2} = \cdots = \beta_3 = 0$	7	95.89	0.000	86.81	0.000
(b) $\beta_{-3} = \beta_{-2} = \beta_{-1} = 0$	3	3.00	0.392	3.91	0.272
(c) $\beta_0 = \beta_1 = \beta_2 = \beta_3 = 0$	4	85.56	0.000	80.68	0.000

Under the null hypotheses (a) and (b), the normalization represented by Eq. (2) also implies that $\beta_{-4} = 0$.

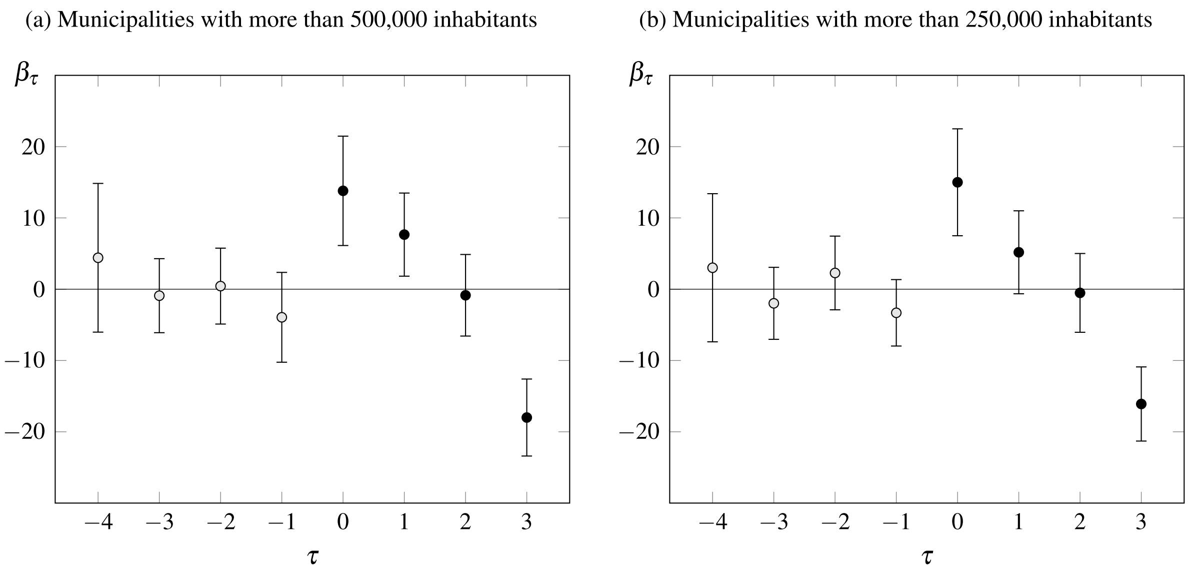

Fig. 2. Relative excess of scrappings by quarter. Point estimates from Eq. (1) showing average excess of scrappings in the postal codes city of Madrid (excluding the LEZ), relative to postal codes in other Spanish municipalities not affected by the LEZ. The estimates are obtained using the normalization given in Eq. (2). Vertical bands represent the 95% confidence intervals for each estimated coefficient.

and second quarters after the policy is implemented, respectively. These outcomes contrast notably with those obtained for the last quarter considered in our sample (i.e., September 2019 to November 2019). If we consider as controls the municipalities with more than 500,000 and 250,000 inhabitants, the corresponding coefficients suggest that the relative amount of scrappage falls by about 12.47% and 11.15% respectively.

An overview of the evolution of the above mentioned coefficients is presented graphically in Fig. 2. In short, we find that excess of scrapped vehicles increased significantly and temporarily in the postal code districts within the municipality surrounding the LEZ during the first two quarters after the regulation was adopted. We also find a subsequent reduction in the relative amount of scrapping in the fourth quarter of this intervention, probably as a consequence of the aforementioned scrapping anticipations. As expected, these significant changes in the relative levels of scrapping after the intervention imply the rejection of any null hypothesis that involves equality to zero of the associated parameters. Finally, we also proposed a hypothesis to test if the cumulative excess of the scrapping after the four post-policy quarters is statistically equal to zero. Because the *p-value* associated with this hypothesis is 0.786 and 0.704 when cities with populations of more than 500,000 and 250,000 inhabitants are respectively used as controls, it cannot reasonably be rejected. It is therefore suggesting that the overall effect of the urban policy intervention vanished completely in one year, which we consider to be an interesting result for the purpose of this research.

4.3. Further evidence based on a triple difference model specification

The results from the previous sub-section show that scrappings in Madrid evolved differently from the other Spanish cities coinciding with the implementation of *Madrid Central*. The objective of this new sub-section is to explore whether we can strengthen the evidence of causality between this excess scrapping and the implementation of the LEZ. For this purpose we take into consideration that there are two types of vehicles, which from the owners' perspective are very similar, but which are subject to different restrictions under the rules of *Madrid Central*, namely gasoline-engine and diesel-engine vehicles registered from 1 January 2001 to 31st December 2005 (see Fig. 3). Gasoline-engine vehicles (type B) receive the official environmental label B, and have permission to access the LEZ for the purpose of parking in private and public designated areas, while diesel-engine vehicles (type A) have no environmental label and, consequently, are denied access (including car park use).

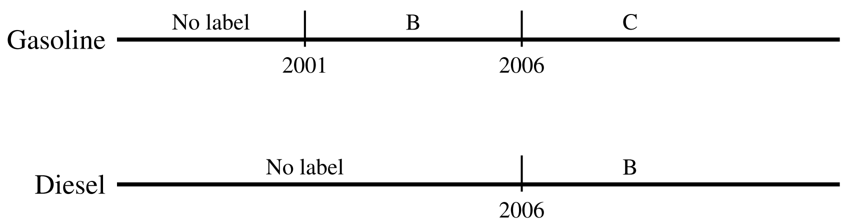

Fig. 3. Environmental labels by engine type and year.

Table 4
Results for label B vehicles and for differences between vehicle types.

	Equation (3a)		Equation (4)
β^B_{-4}	−0.34 (0.64)	β^D_{-4}	−1.86 (1.07)*
β^B_{-3}	−0.09 (0.59)	β^D_{-3}	−1.29 (0.93)
β^B_{-2}	0.16 (0.71)	β^D_{-2}	2.24 (1.07)**
β^B_{-1}	0.27 (0.65)	β^D_{-1}	0.91 (1.08)
β^B_{0}	0.21 (0.76)	β^D_{0}	8.53 (1.90)***
β^B_{1}	−0.70 (0.64)	β^D_{1}	5.98 (1.54)***
β^B_{2}	1.21 (0.84)	β^D_{2}	1.92 (1.36)
β^B_{3}	−1.38 (0.87)	β^D_{3}	0.50 (1.47)
Obs.	1432		1432
N	179		179
T	8		8

Regressions include postal code and time fixed effects considering the postal codes within the Spanish mainland municipalities with more than 500,000 inhabitants. Parameters before the policy intervention are normalized according to an equation analogous to (2). Clustered standard errors at postal code level are presented in parenthesis.

*Denote statistical significance at the 10% level.

**Denote statistical significance at the 5% level.

***Denote statistical significance at the 1% level.

Taking these considerations into account, we can rewrite the event study models represented by Eq. (2) for each of the vehicle types:

$$s^B_{it} = \sum_{\tau=-4}^{3} \beta^B_\tau Z_i D_{t_0+\tau} + \alpha^B_i + \lambda^B_t + \epsilon^B_{it} \tag{3a}$$

$$s^A_{it} = \sum_{\tau=-4}^{3} \beta^A_\tau Z_i D_{t_0+\tau} + \alpha^A_i + \lambda^A_t + \epsilon^A_{it} \tag{3b}$$

where s^B_{it} and s^A_{it} are, respectively, the number of scrapped gasoline-engine and diesel-engine vehicles registered between 2001 and 2006 in postal code district $i = 1, 2, \dots, N$ and quarter $t = 1, 2, \dots, T$. We use t_0 to denote the quarter that immediately follows the introduction of the LEZ. Therefore, if the traffic restrictions of *Madrid Central* had a greater impact on scrapping of vehicles with no environmental label, the differences $\beta^D_\tau = \beta^A_\tau - \beta^B_\tau$ would be positive. Subtracting (3a) from (3b) yields a specification that allows us to directly estimate these differences:

$$d_{it} = \sum_{\tau=-4}^{3} \beta^D_\tau Z_i D_{t_0+\tau} + \alpha^D_i + \lambda^D_t + \epsilon^D_{it} \tag{4}$$

where

$$d_{it} = s^A_{it} - s^B_{it}, \quad \beta^D_\tau = \beta^A_\tau - \beta^B_\tau, \quad \alpha^D_\tau = \alpha^A_\tau - \alpha^B_\tau,$$
$$\lambda^D_\tau = \lambda^A_\tau - \lambda^B_\tau, \quad \epsilon^D_\tau = \epsilon^A_\tau - \epsilon^B_\tau.$$

The OLS estimation results for both vehicles with environmental label B (Eq. (3a)) and differences between types of vehicles (Eq. (4)), using the sample of postal code districts within municipalities with more than 500.000 inhabitants, are shown in Table 4. Fig. 4 provides an overview of the results by representing our point and interval estimations of β^B_τ and β^D_τ. In addition, Table 5 presents the outcomes of the joint significance test on the parameters. Specifically, we show the results for the hypotheses of equality of all the parameters, of those corresponding to the quarters prior to the LEZ, and of those associated with the quarters after its implementation.

Table 5
Joint significance test.

H_0	d.f.	Equation (3a)		Equation (4)	
		χ^2	p-value	χ^2	p-value
(a) $\beta^l_{-3} = \beta^l_{-2} = \cdots = \beta^l_3 = 0$	7	7.06	0.423	30.95	0.000
(b) $\beta^l_{-3} = \beta^l_{-2} = \beta^l_{-1} = 0$	3	0.43	0.934	7.62	0.055
(c) $\beta^l_0 = \beta^l_1 = \beta^l_2 = \beta^l_3 = 0$	4	5.70	0.223	25.37	0.000

The parameter superscript l is equal to B in Eq. (3a) and D in Eq. (4). Under the null hypotheses (a) and (b), the normalization represented by Eq. (2) also implies that $\beta_{-4} = 0$.

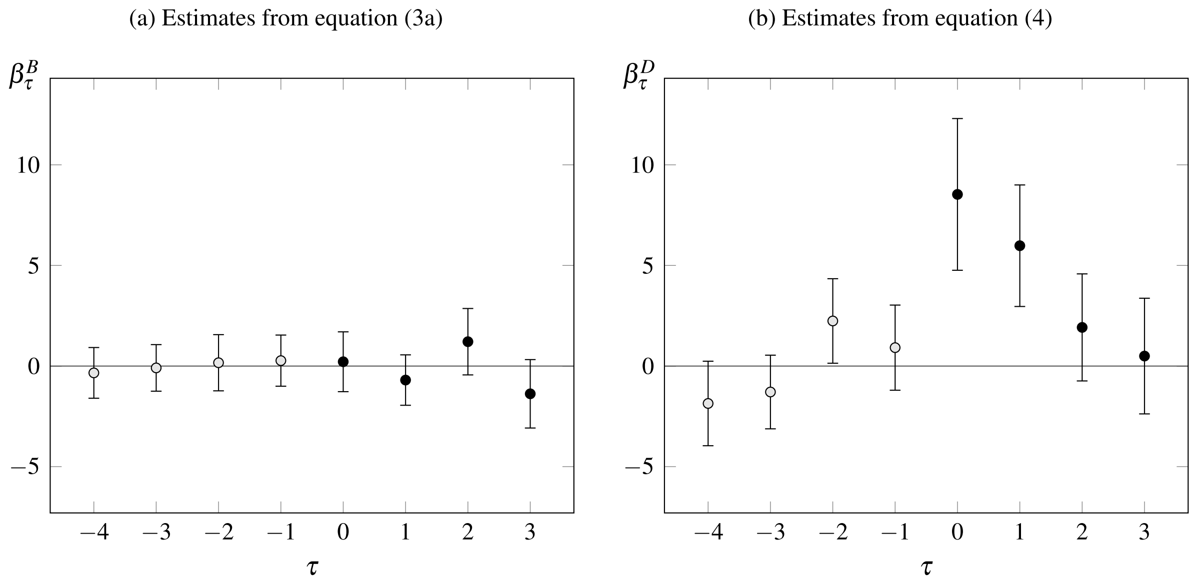

Fig. 4. Relative excess of scrappings for vehicles with label B and for differences between vehicles types The points show the relative excess of scrappings in the city of Madrid (excluding the LEZ), controlling by postal codes within the Spanish mainland municipalities with more than 500.000 inhabitants and normalizing parameters before the urban policy intervention according to Eq. (2). Vertical bands represent the 95% confidence intervals for each estimated coefficient.

As we can see, the results from the model applied to gasoline-engine vehicles with label B (represented by Eq. (3a)) yield no significant parameter. Hence, all the corresponding equality tests cannot be rejected, which means that we cannot find essential differences between the scrappings in Madrid and in the other Spanish cities. In other words, our results suggest that the significant excess of scrapped vehicles after the implementation of the urban measure revealed in Section 4.2 cannot be attributed to these gasoline-engine vehicles with environmental label B, which can access parking designated areas within the LEZ. These results contrast with those obtained from the triple difference model specification (represented by Eq. (4)). Specifically, parameter β^D_{-2} corresponding to this model, which is significant at the 5% level, reveals a certain effect prior to the effective implementation of the LEZ. That is, two quarters before this urban measure, the impact on those vehicles for which access is totally prohibited (i.e., without any environmental label) is seen to be somewhat greater than on those vehicles with partial restrictions (with environmental label B). This outcome seems quite reasonable since an intense information campaign about *Madrid Central* was run in the summer of 2018, coinciding with the quarter with which the parameter is associated.[7] The larger estimates are for β^D_0 and β^D_1, the two quarters immediately following the introduction of the LEZ which, in turn, are highly statistically significant. Thus, in both quarters, the results suggest that the urban measure has a greater effect on the scrapping of vehicles for which access to the LEZ is totally prohibited in relation to those with partially restricted access. Therefore, the hypothesis of equality of parameters associated with the quarters following the urban policy intervention is clearly rejected. In summary, it must be taken into account that there is evidence to show that more scrapping takes place after the policy was implemented. Previous research also reveals that there is a particularly significant effect on vehicles for which access is prohibited, that is, on diesel-engine vehicles, even though they are known to last longer and, therefore, have a lower depreciation than gasoline-engine vehicles (Gilmore and Lave, 2013; Belzowski, 2015).

[7] This effect prior to the implementation of the measure is not clearly reflected in the analysis offered in Section 4.2. Please note that we are now just exploring the differences in terms of scrapping between type A and type B vehicles within their specific segment registered between 2001 and 2006. Thus, the divergence between the result depicted in Figs. 4(b) and 2(a) would indicate that the higher scrap rate in type A vehicles for this specific age segment is not enough to find a significant increase in the ratio of total scrappings.

5. Concluding remarks

The main motivation for this paper was the level of air pollution from nitrogen oxides and breathable particulate matter emitted by old combustion vehicles. Scrapping of older vehicles can be a useful tool to address this problem, and in turn, it can have beneficial repercussions on road safety. It is not surprising, therefore, that there is abundant literature on the relationship between implementation of accelerated vehicle retirement programs and scrapping behavior. The literature reports that the effectiveness of these programs is transitory and that, in general, they are barely justified when costs associated with subsidies or tax reductions are considered in the analysis. On the other hand, in recent years researchers have been increasingly interested in knowing the effect of LEZs on the levels of contamination inside and around them. The literature reveals LEZs positively affect air quality, although their impact depends on aspects such as the intensity of restrictions, characteristics of the city in which they are implemented, or their relative geographical dimension. Nevertheless, to our knowledge, no studies have explored the extent to which the creation of a LEZ could affect the decisions to scrap older vehicles.

Because a growing number of European cities are now developing new projects to close their centers to the most polluting vehicles, the evaluation of the effects of these urban policy interventions is timely. In this context, Spain offers a paradigmatic example because by law, all cities with more than 50,000 inhabitants must incorporate a LEZ by 2023 at the latest. In addition, all cities with more than 20,000 inhabitants that report relatively high levels of air pollution according to national regulations will also have to incorporate these measures. With the purpose of providing the first evidence on the possible impact of LEZ on scrapping decisions, we examined the case known as *Madrid Central*. The empirical analysis entailed applying a quasi-experimental design to a large volume of information from the decisions to scrap passenger cars and light commercial vehicles with gasoline and diesel combustion engines. To this end, we constructed a panel data set consisting of the numbers of these vehicles scrapped by postal code in each quarter of the period between December 2017 and November 2019, thus covering the four quarters before and after this access regulation came into force.

We used two empirical approaches to meet the paper's objectives. The first approach aimed to offer an overview of the possible excess scrapping, compared to the control groups, in the city of Madrid (excluding the area corresponding to the LEZ due to its peculiarities). In general terms we found that the scrapping decisions were not significantly higher during the period when the urban policy intervention was announced, but there was a clear variation in the relative amount of scrappage during the quarters immediately after it came into force. This outcome, which is robust to changes in controls based on scrapping in postal code districts of large cities, deserves more detailed comment. During the quarter beginning on the day the LEZ came into force, we found a significant relative excess of scrapping of about 8%. In the subsequent quarter evidence on the positive excess is weaker, falling by almost half. In the third quarter after the measure, accelerated vehicle retirements came to a halt, suggesting that beyond this point the urban policy intervention was no longer effective for this purpose. Finally, a significant drop in the relative number of scrappings was seen in the last quarter of the year after the regulation came into force, offsetting the aforementioned excess scrapping. Although we cannot establish what is the main determinant of a lower scrappage rate in this last quarter, this outcome seems more consistent with the simple consequence of anticipation on the decision regarding the scrapping of old vehicles during the first two quarters of the existence of the urban measure than with other potential factors (such as incorrect conjectures made by owners on the possible relaxation of restrictions in the LEZ because of the change of local government in the previous quarter). In the second approach, we explored whether we could strengthen the evidence discussed above that excess scrapping was actually caused by the traffic restrictions in *Madrid Central*. For this purpose, we focused only on vehicles registered in the same period (from 1 January 2001 to 31st December 2005), but differentiated by the access they had to the LEZ. Specifically, gasoline-engine vehicles (with environmental label B) had access to the parking areas in the LEZ, whereas diesel-engine vehicles (with no label) were denied access. While no excess scrapping was found for the first group, an excess was found for the second group during the first two quarters after the LEZ was implemented.

In summary, our analysis suggests that creating new LEZs has some potential to encourage the withdrawal of older vehicles within their traffic areas of influence. It is reasonable to think that such interventions will contribute temporarily to both greater traffic safety and to further reduce potential emissions from the vehicle fleet, which, according to previous research, will add to the benefits of improving air quality inside the LEZ. Otherwise, despite these gains, a LEZ also implies limitations and social costs that should be considered in the decision to adopt it. The transitoriness of the effect is perhaps one of the major limitations. Hence, it should be kept in mind that new impulses to promote scrapping will require the periodic introduction of new traffic restrictions on the type of vehicles or the area of coverage. The gradual expansion of LEZ across the whole of Madrid, which is expected to culminate in 2025 with the declaration of a LEZ for the entire city (i.e., *Madrid 360*), can be considered a good example. Moreover, the greater incidence of the urban measure on the poorest social stratum, whose members are generally the owners of the oldest vehicles, or the waste and emissions generated in the scrapping procedure itself, are some relevant examples of social costs. It is obvious that a full assessment of these costs is no easy task. An analysis exclusively focused on comparing certain models of LEZs and accelerated vehicle retirement programs, from the point of view of their cost-effectiveness, could presumably be more straightforward and quite timely given the number of papers that are critical with these popular programs. Since the LEZs do not involve any costs in terms of subsidies or tax exemptions, they could be considered a potentially suitable alternative.

CRediT authorship contribution statement

Jacint Balaguer: Methodology, Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Project administration. **José C. Pernías:** Methodology, Conceptualization, Validation, Investigation, Formal analysis, Data curation. **Jordi Ripollés:** Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization.

Data availability

Data to replicate our results are available at https://doi.org/10.17632/f38zrhc2k7.1.

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