Have Low Emission Zones slowed urban traffic recovery after Covid-19?

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Abstract

This paper bridges the gap between the literature on the pandemic's effects on mobility and the literature on the impact of low emission zones (LEZ). Using data for large European cities in the period 2018-2021, we examine whether LEZs may explain differences in the recovery patterns of traffic in European cities after the shock of Covid. Controlling for several city attributes, we examine whether LEZ cities are less congested before and after the pandemic in comparison to non-LEZ cities. LEZs may have been more effective in reducing congestion after the pandemic because the fleet renewal process has slowed down or, alternatively, LEZs may be a proxy of unobservable factors related with attitudes of governments and citizens towards a sustainable mobility. Our results validate the traffic-mitigating role of the LEZ after the Covid-19 pandemic, although such result only holds for the pioneering LEZ cities. Hence, the traffic-mitigating role of the LEZ after the Covid-19 pandemic seems to be related to unobservable attributes that influenced the early decision to implement a LEZ. In this regard, we also find that LEZs may have induced a change in local attributes related to sustainable mobility given that we do not find differences between LEZs decided at the local or regional level.

Keywords: Low Emission Zones; Congestion; Traffic; Access restrictions; Sustainability; Cities.

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Introduction

The Covid-19 pandemic has had a very significant impact on mobility due to the restrictions imposed by governments, the fear of contagion and the spread of teleworking (Albalate, *et al*., 2022). This fall in mobility was very strong for all modes of transport in 2020, particularly in the spring, which coincides with the strict lockdown resulting from the first wave of the pandemic. These impacts have been even stronger in urban areas, where the high levels of social interaction accentuated the effects of the pandemic, also due to the fact that the largest volume of trips by both public or private transport are concentrated in urban areas. However, the evolution of car traffic in 2021 was more heterogeneous and there is a lack of evidence about the causes behind the different recovery patterns of car traffic between cities.

Before the pandemic, there was growing concern about the excessive volume of cars in urban mobility. Indeed, the great volume of private transportation in large cities generates significant negative externalities in terms of congestion, pollution, accidents, occupation of public space and noise. In this respect, in the short term, the pandemic has had a positive collateral effect, since fewer cars have meant less pollution (Venter *et al*., 2020; Llaguno-Munitxa & Bou-Zeid, 2022) and less congestion (Winchester *et al*., 2021; Chen & Steiner, 2022).

In this paper, we focus our attention on congestion. Urban congestion results in traffic jams that increase travel time representing a huge economic cost. For example, a recent study by the European Commission (2019) revealed that congestion due to road transport in all European Union countries costs €271 billion per year.

In addition, congestion aggravates other negative externalities. There is a particularly clear relationship between congestion and pollution (Barth and Boriboonsomsin, 2008; Beaudoin *et al.*, 2015, and Parry *et al.*, 2007). Albalate and Fageda (2021) also show that higher levels of congestion may lead to worse safety performance outcomes.

Although there is a growing literature on the effects of the Covid-19 pandemic on mobility, most studies are based on surveys or descriptive data for 2020. As expected, several studies find a reduction in the demand of transportation due to the increasing use of teleworking (Falchetta *et al*., 2021; Mouratidis *et al*., 2021, Barrero *et al*., 2020; Brick *et al*., 2020). However, the demand for public transport has fallen more sharply than that of private transport due to fear of contagion, and private transportation modes are recovering to pre-Covid levels faster (Albalate et al., 2022). Indeed, evidence has been found of a greater preference for private transport over public transport after the lockdown in studies in very different geographical areas (Abdullah *et al*., 2021; Eisenmann *et al*., 2021, Przybylowski *et al*., 2021, Dias et al., 2021, Dingil *et al*., 2021; Echaniz *et al.*, 2021, Awad-Nuñez *et al.*, 2021, Aloi *et al.*, 2020, Basu & Ferreira, 2021). Moreover, another strand of literature has shown that the pandemic has caused an increase in suburbanization or, in other words, a shift of residence from the city centre to the suburban area (Chun *et al*., 2022; Murat *et al*., 2021; Stawarz *et al*., 2022). Other studies find a higher decrease in the mobility of high-income citizens (Mejía *et al.*, 2021) and an increased proportion of traffic made up of commercial vehicles (Villa & Monzón, 2021).

Overall, the short-term effect of the pandemic has undoubtedly been a sharp drop in traffic volumes, but the long-term effects are highly uncertain, and may even end up involving an increase in mobility (Currie *et al*., 2021; Eliasson, 2022; Zhang *et al*., 2021). On the one hand, the increasing use of teleworking may reduce car traffic and congestion. On the other, a more negative perception of public transport may be maintained over time, with the consequent increase in the modal share of private transport and, hence, an increase in congestion. The pandemic may also accelerate the process of suburbanization in large cities, in the sense that many citizens will move to live in smaller municipalities in the metropolitan area. Suburbanization can increase the number of trips made from other municipalities into the central city. As public transport options are generally worse in terms of traffic penetration than mobility within cities, suburbanization may lead to increased dependence on cars and longer trips. In addition, traffic growth may be expected because of the increased number of commercial vehicles generated by the e-commerce boom.

Thus, it may be even more necessary than before the pandemic to implement policies aimed at reducing car dependence (and its associated externalities), such as investment in public and non-motorized transport, price-based measures (tolls, parking costs, etc.) and restrictions via quantities (low emission zones, reduction of space for cars, etc.).

Of the policies implemented, low emission zones (LEZ) are the most popular quantity-based measure in Europe. LEZs ban polluting vehicles (i.e., those not complying with emission standards) from city centres. Several studies have analysed the effects of LEZs on pollution. Previous studies for German cities suggest that LEZs can be effective at improving air quality. Malina and Scheffler (2015) analyse the impact of LEZs on PM10 emissions with data for the period 2000-2009, finding a reduction of 13%. Also focusing on PM10 emissions and using data at a detailed geographical scale for 2008-2010, Wolff (2014) finds an average reduction of 9%. Morfeld *et al.* (2014) also find LEZs have a significant impact on reducing NO, NO_2, and NOx. The magnitude of the impact is around 4%.

Some other studies examine the effect of LEZs on individual cities by comparing pollution levels before and after their implementation. Panteliadis *et al.* (2014) study the LEZ implemented in Amsterdam, which gradually banned heavy-duty vehicles based on their emission category. They find a reduction in the concentration of different pollutants, ranging from 4% for NO_2 and NO_x, up to 10% for PM10. Ellison *et al.* (2013) study the case of London, where an emission standard was imposed on trucks, coaches and buses in an area covering most of Greater London. They show that PM10 concentrations within the limits of the LEZ dropped by 2.46%-3.07%, compared to a lower decrease of 1% in limiting areas; however, no discernible differences are found for NO_x concentrations. Cesaroni *et al.* (2012) analyse intervention policies in Rome, including the exclusion of all cars from the historical city centre and the prohibition of old diesel vehicles within the railway ring. In the intervention area, they find a reduction in PM10 and NO_2 of 33% and 58%, respectively (but the results are modest city-wide). Salas et al. (2021) find that the LEZ in the city of Madrid, where an emission standard to access the city centre was imposed on all vehicles, reduced the NO_2 levels by 11 $\mu g/m^3$ in the restricted area. Gonzalez et al. (2022) and Peters et al. (2022) find that LEZ has promoted the use of cleaner vehicles also in Madrid.

Some recent studies also find evidence that the reduction of pollution due to the implementation of LEZs in Germany has had positive –albeit modest– health effects (Gehrsitz, 2017; Pestel & Wozny, 2021). Similarly, Poulhès & Proulhac (2021) find positive health effects of LEZ in Paris.

The literature on the effects of LEZs on congestion is much scarcer. Bernardo *et al.* (2021) do not find evidence that LEZs reduce congestion in a study that considers several European urban areas. Taking a different approach, Tassinari (2022) reaches the same conclusion in a detailed analysis for the city of Madrid. Moreover, Fageda *et al.* (2022) develop a model that provides the rationale for the prevalence of LEZs instead of tolls in high-income cities.

Thus, previous literature suggests that LEZs have been effective in reducing pollution but not congestion. The main reason behind the reduction in pollution is that LEZs have spurred the renewal of the car fleet from older to new and more efficient vehicles. This renewal does not curb congestion, as the newer cars can enter the restricted area. Another aspect as to why newer cars may reduce pollution but not reduce congestion is related to the rebound effect of fuel efficiency. Newer cars are more fuel efficient, so the marginal private cost of driving is lower, which could lead potentially to a higher quantity of trips.

This paper contributes to the literature by bridging the gap between the literature on the pandemic's effects on mobility and the literature on the impacts of LEZs. Using data for large European cities in the period 2018-2021, we examine whether the implementation of LEZ policies may explain differences in the recovery patterns of traffic in European cities after the shock of Covid. Indeed, we examine whether LEZ cities have less congestion before and after the pandemic in comparison to non-LEZ cities, controlling for several city attributes –and other traffic restrictions– that may influence congestion.

We find evidence that LEZs reduce congestion after the pandemic but not before. Two alternative hypotheses may explain the effectiveness of LEZs in reducing congestion after the pandemic. On the one hand, the fleet renewal process could have slowed down after the pandemic. On the other hand, governments and citizens in LEZ cities may have better attitudes towards a sustainable mobility after the pandemic, for example increasing the use of public transportation and teleworking. Our analysis provides more evidence in favour of the second hypothesis given that the reduction in congestion concentrates in the pioneering LEZ cities.

The rest of the paper is organized as follows. The next section explains the data and variables used in the econometric analysis. Then, we show the methods and empirical equations that we estimate and discuss the identification strategy. This is followed by a section on the results of the econometric estimates. The last section is devoted to a discussion and concluding remarks.

Data and variables

Our analysis draws on a novel database created for the purpose of this research with information for 144 cities from 25 different countries in the European Union (plus the United Kingdom and Switzerland) between 2018 and 2021.[1] Our dependent variable is the level of congestion experienced in these cities. Data for congestion were obtained from TomTom (https://www.tomtom.com/en_gb/tra_cindex), measured as the additional travel time a vehicle needs to undertake as compared to a free-flow situation. TomTom obtains real data from drivers' travel time from every city where they operate. Based on actual GPS-based measurements for each city, TomTom registers data from local roads, arterials and highways. Several recent articles have used this measure of congestion (see Albalate and Fageda, 2021; Bernardo *et al.*, 2021, Fageda, 2021; Winchester *et al.*, 2021, among others).

Although the variable measures the average congestion for a given year, which has the obvious limitation that it hides substantial differences between peak and off-peak periods –as well as seasonality–, it seems appropriate for the purpose of this research, which does not focus on the dynamics of congestion but on the average reaction of traffic after Covid-19. This logarithm of

[1] The sample includes all cities with over 300,000 inhabitants with congestion data available. We only exclude cities with road pricing schemes, which are stricter access restriction policies that may confound the effect of LEZs and, due to the low number of such schemes, do not offer enough variability to be included as a covariate.

congestion is regressed on the presence of traffic restriction regulations, and a vector of covariates. All of them are described below.

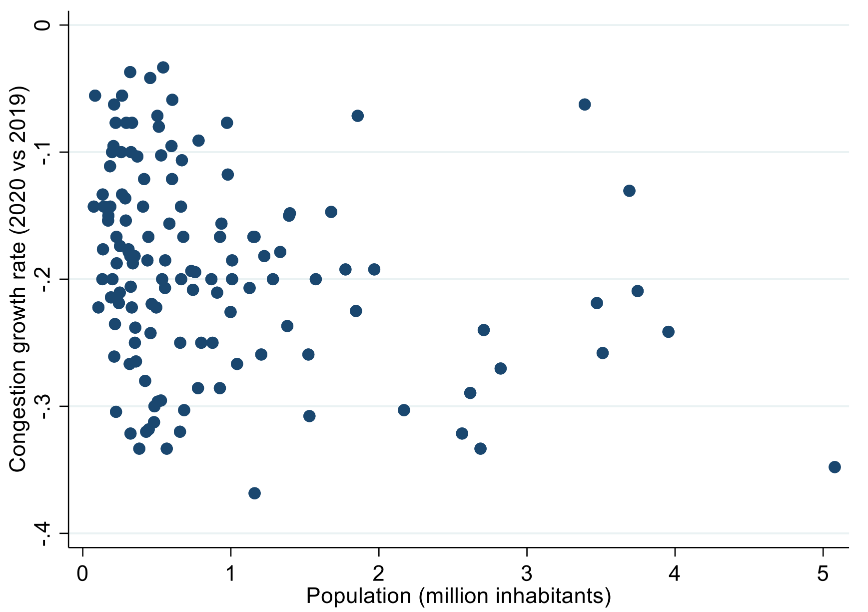
The traffic restriction variables considered in our analysis are binary variables, with 1 denoting the presence of a particular traffic restriction and 0 otherwise. D^{LEZ} denotes the presence of LEZs, which is our main variable of interest, while D^{LTZ} refers to limited traffic zones –other traffic access regulations– and acts as a necessary control variable. The data used to construct these variables were mainly obtained from the database Urban Access Regulations in Europe (https://urbanaccessregulations.eu/) and the authors' own research. The D^{LEZ} variable is also divided into different categories in our empirical analysis. First, we distinguish between D^{WIDE} and D^{CITY}. They are also binary variables that distinguish whether the LEZ has a large territorial scope, or is delimited within the core area of the city. This distinction is made to potentially capture heterogeneous effects of the role of LEZs according to their territorial scope**.** Furthermore, we distinguish between D^{NEW} and D^{OLD}. They are binary variables that distinguish whether the LEZ was implemented in the period that goes from 2008 to 2015, or later. This will allow us to provide evidence about the mechanism that drives the result for the LEZ variable. It should also be noted that we just consider LEZ policies that apply to all types of vehicles, not just commercial vehicles.

Our sample includes 45 LEZ cities. LEZ programmes have been widely implemented in Belgium (Antwerp, Brussels, Gent), Germany (Berlin, Bochum, Bonn, Bremen, Cologne, Dortmund, Düsseldorf, Duisburg, Essen, Frankfurt, Hamburg, Hannover, Karlsruhe, Leipzig, Münster, Munich, Stuttgart, Wuppertal) and Italy (Bologna, Brescia, Florence, Genoa, Milan, Modena, Naples, Palermo, Parma, Reggio Emilia, Rome, Torino, Verona). They have also been implemented in large cities in other countries (Barcelona, Lisbon, Madrid, London, Oslo, Paris, Prague, Rotterdam, Stockholm, and Utrecht). Note here that London, Milan, Palermo, and Stockholm are the only cities in Europe that apply congestion tolls.

It is also relevant to remark that the first LEZs were implemented between 2008 and 2015, in most German cities with LEZs, in several Italian cities and in Lisbon and Utrecht. In contrast, some cities in our sample (Barcelona, Brescia, Brussels, Gent, London and Stockholm) implement LEZ after 2018. Thus, the LEZ variable for these cities does not always take the value one in the period considered.

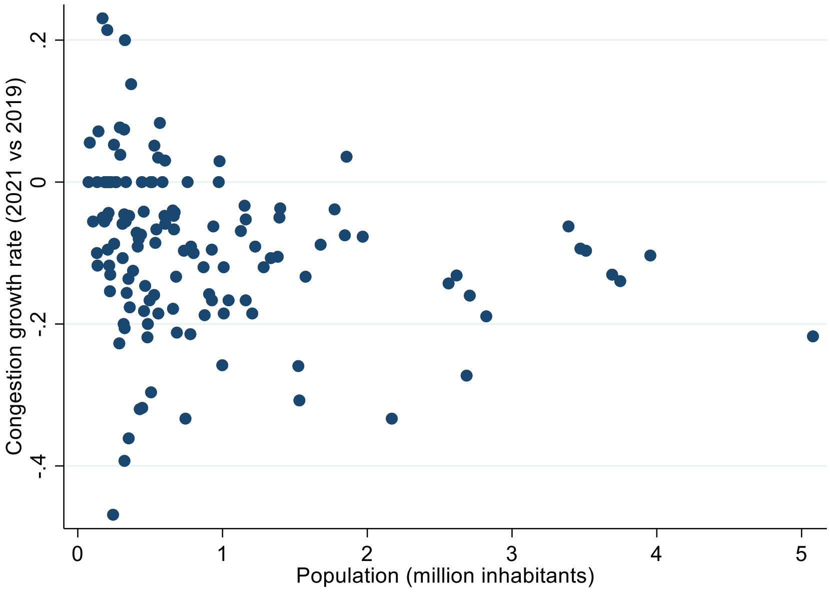
Figure 1 shows the congestion growth rate in 2020 in relation to 2019 for our sample of European cities. As expected, all cities have less congestion in 2020, with decreasing rates that, in most cases, range from -10% to -30%. More interestingly, Figure 2 shows the growth rate of congestion in 2021 in relation to 2019. A high degree of heterogeneity can be observed in the growth rates of congestion after Covid. In total, 20 cities have recovered the levels of congestion that they had in 2019, while another 20 cities have even higher levels of congestion in 2021 than those recorded in the pre-pandemic period. The rest of the cities still have lower levels of congestion but with high variability in the growth rates, ranging from -3% to -46%.

Figure 1. Congestion growth rate (2020 vs. 2019)



Note: We exclude London and Paris as population outliers to facilitate the interpretation of the figure. The growth rates of London and Paris were -18% and -1%, respectively.

Figure 2. Congestion growth rate (2021 vs. 2019)



Note: We exclude London and Paris as population outliers to facilitate the interpretation of the figure. The growth rates of London and Paris were -13% and 8%, respectively.

This strong heterogeneity in traffic recovery patterns between European cities could be related to the application of different traffic restriction policies, the identification of which is the main objective of this article. Figures 3 and 4 provide suggestive evidence of the role that such policies may have had on the recovery patterns in 2021.

Figure 3 displays the median spline of the relationship between congestion over time comparing cities with LEZs to areas without. The 2021 traffic recovery seems to be descriptively lower in the case of areas with LEZs. Figure 4 depicts a stricter comparison between cities with only LEZs –excluding those with also limited traffic zones regulations– and cities with neither LEZs nor limited traffic zones. Again, the rate of increase of traffic for cities with LEZs seems to be lower than for the comparison group. However, these are just bivariate relationships that neglect confounding factors and other determinants of congestion. A multivariate approach is needed.

Figure 3. Median spline of the relationship between congestion and time, by LEZ regulation.

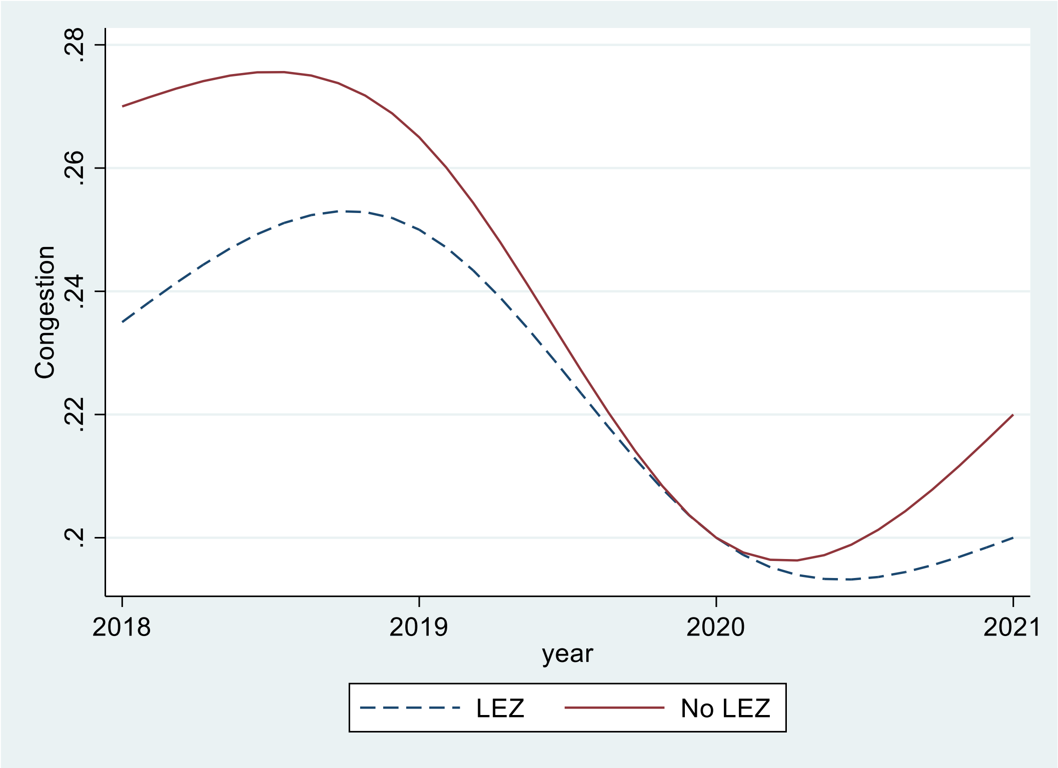
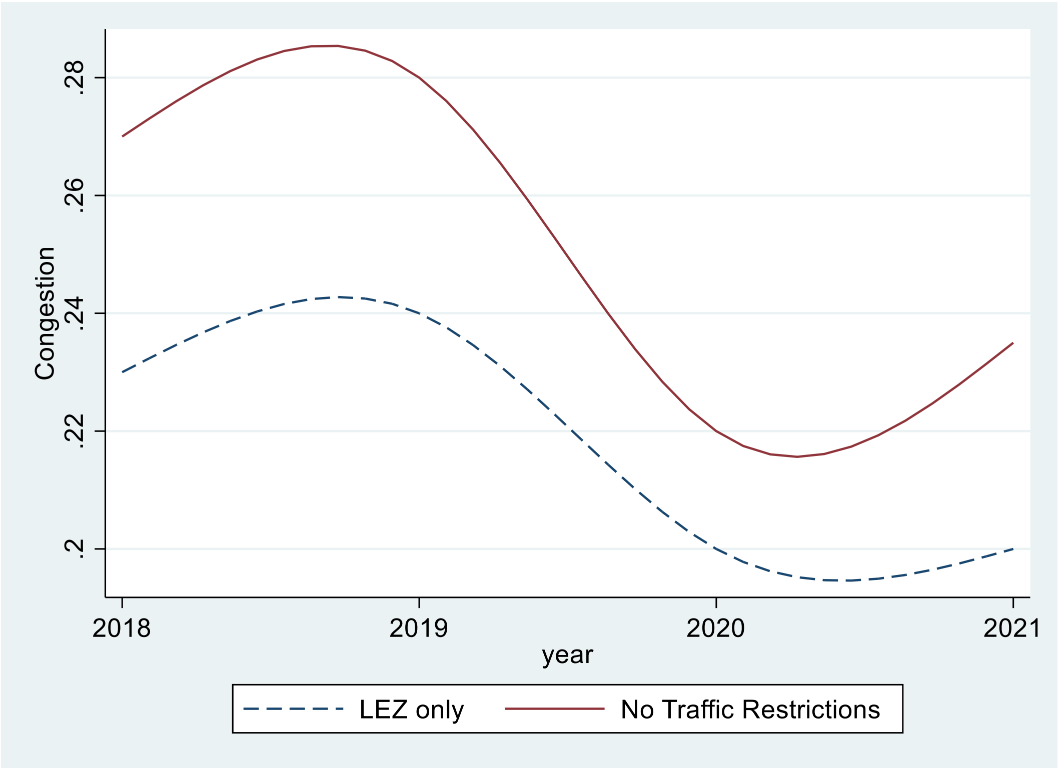


Figure 4. Median spline of the relationship between congestion and time, by LEZ regulation (against no traffic regulations cities).



In this regard, the vector of covariates in our multivariate analysis is composed of seven variables, which are expected to determine the level of congestion in cities. The main sources of theses variables are the OECD Regions and Cities Database (https://stats.oecd.org/Index.aspx?DataSetCode=CITIES) and Eurostat (https://ec.europa.eu/eurostat/data/database).

Public transportation supply is proxied by two variables: firstly, the endowment of surface railways per capita (per thousand inhabitants) (*Rail*) as a proxy of capacity; and secondly, the number of lines of underground rail services (*Metro*) as an indicator of accessibility. We expect a negative relationship between congestion and public transportation supply because public transportation is the most direct alternative to private transportation. Note that this variable is only available for 2021, so that we assume the same values for the rest of years. In this regard, we may expect modest changes in public transport supply in the short four-years period that we consider (with two of the years affected by the pandemic).[2]

Private transportation demand is captured by the *Motorization* variable, which is constructed as the number of cars per 1,000 inhabitants. We expect a positive relationship between motorization and congestion given the stock of cars is highly correlated with their use, and the latter with congestion.

Socioeconomic and demographic variables are also considered in our analysis. The number of inhabitants (in thousands) is used to build our *Population* variable, which captures the size of potential mobility needs of a city. We expect more populated areas to be prone to suffering from high congestion. The GDP per capita (in thousands) is also included as a control, to account for income, but we do not have a particular expectation about the direction of its effect on congestion. This is firstly because higher income is usually associated with higher use of private

[2] Unfortunately, data in Europe of public transit ridership are not available at the city-level. It may be the case that some local agencies provide the information on public transit ridership but collecting this information from different sources with different criteria and different time periods covered would not be feasible and probably not effective given that the number of cities with available information would be small.

transportation; however, secondly, higher GDP per capita is also associated with better transportation systems and public transportation networks and services.

Urban form might also be a relevant determinant of traffic demand and mobility patterns, which might also influence the level of congestion. We use two variables to measure this relationship. Firstly, the *Urban Sprawl* variable accounts for the core-periphery structure of the metropolitan area. This is the ratio between the population living in the functional area of the city over the population living just in the city area. Thus, we expect this variable to be positively correlated with congestion if people living in the functional areas have higher mobility needs into and out of the main city, thereby increasing congestion. Alternatively, we would expect a negative correlation if the fact that there are more people living in the functional areas implies lower density in the core city, where congestion is more likely located. Secondly, we use the *Polycentric* variable to account for differences between monocentric and polycentric cities. Our expectation is that monocentric areas are more prone to suffering from congestion due to the concentration of activity in the central business district than polycentric cities.

Table 1 displays the main descriptive statistics of the variables employed in our empirical analyses, while table 2 provides the mean values for the different sub-samples according to the type of LEZ.

Table 1. Descriptive statistics of variables employed.

Variables	Mean	Std. dev.	Min	Max
Congestion (additional travel time as compared to a free-flow situation	24	7.38	8	52
LEZ (dummy variable)	0.27	0.45	0	1
LTZ (dummy variable)	0.26	0.44	0	1
Rail (kms per 1,000 inhabitants)	0.21	0.36	0	2.56
Metro (number of lines)	1.91	3.17	0	16
Motorization (cars per 1,000 inhabitants)	556	86	275	814
Population (number of 000 inhabitants)	1.426	1.538	188	11.236
GDP (Euros per capita)	33.447	10.429	8.820	84.940
Urban sprawl (ratio population city/functional area)	1.90	1.96	1.02	5.19
Polycentric (dummy variable)	0.16	0.37	0	1

Table 2. Mean values for different sub-samples according to LEZ type.

Variables	Wide LEZ	Central LEZ	New LEZ	Old LEZ	No LEZ
Congestion	24.14	23.64	24.25	23.6	24.27
Rail	0.36	0.29	0.36	0.29	0.19
LTZ	0.45	0.38	0.57	0.57	0.22
Metro	4.01	4.62	4.12	4.52	1.04
Motorization	556	572	563	564	553
Population	2880	2139	2693	2253	1132
GDP	36672	37864	34728	39263	32049
Urban sprawl	1.59	1.76	1.71	1.68	1.96
Polycentric	0.44	0.27	0.32	0.36	0.11
Observations	77	93	70	100	411

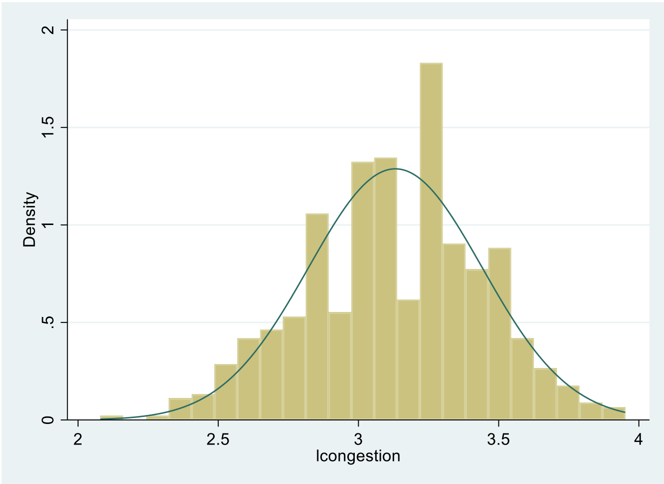
Methods

To evaluate the role of LEZs on traffic congestion, we implement a variety of econometric models, exploiting both the cross section and the short time series of our data. These models estimate the contribution of LEZs to the average congestion. Firstly, we estimate a pooled model with Ordinary Least Squares (OLS). Secondly, we apply different panel data models such as the Generalized Estimating Equations (with Gaussian family), the Random Effects and the Fixed Effects models. Note that the fixed effect model considers city-specific effects that allows controlling for time-invariant unobservable factors like, for example, systematic differences in public transit ridership between cities. Equation 1 displays our baseline specification for these models:

$$\log(Congestion)_{it} = \alpha + \beta D_{it}^{LEZ} + \gamma D_{it}^{LTZ} + \delta_1 \log(Rail)_{it} + \delta_2 Metro_{it} + \delta_3 \log(Motorization)_{it} + \delta_4 \log(Population)_{it} + \delta_5 \log(GDP)_{it} + \delta_6 Urban\_Sprawl_{it} + \delta_7 Polycentric_i + D_t^{2019} + D_t^{2020} + D_t^{2021} + \varepsilon_{it} \quad \textbf{(1)}$$

The average congestion variable was not normally distributed, so we used its log transformation, which produced a normally distributed dependent variable for our analysis (See Figure 5), as confirmed –or at least not rejected– by the Shapiro-Wilk W test for normal data (p-value 0.26). The log transformation also facilitates the interpretation of coefficients as elasticities or semi-elasticities. The Ramsey Reset test for omitted variables also rejected specification errors (Prob > F = 0.4687).

Figure 5. Histogram of the dependent variable log(Congestion).



The baseline specification is later modified to estimate a potential differentiated effect of LEZs depending on their territorial scope and the year of implementation. As displayed in equations 2 and 3 below, the binary variable D^{LEZ} is substituted by two binary variables D^{WIDE} and D^{CITY}, and D^{NEW} and D^{OLD}.

$$\log(Congestion)_{it} = \alpha + \beta_1 D_{it}^{WIDE} + \beta_2 D_{it}^{CITY} + \gamma D_{it}^{LTZ} + \delta_1 \log(Rail)_{it} + \delta_2 Metro_{it} + \delta_3 \log(Motorization)_{it} + \delta_4 \log(Population)_{it} + \delta_5 \log(GDP)_{it} + \delta_6 Urban\_Sprawl_{it} + \delta_7 Polycentric_i + D_t^{2019} + D_t^{2020} + D_t^{2021} + \varepsilon_{it} \quad \textbf{(2)}$$

$$\log(Congestion)_{it} = \alpha + \beta_1 D_{it}^{NEW} + \beta_2 D_{it}^{OLD} + \gamma D_{it}^{LTZ} + \delta_1 \log(Rail)_{it} + \delta_2 Metro_{it} + \delta_3 \log(Motorization)_{it} + \delta_4 \log(Population)_{it} + \delta_5 \log(GDP)_{it} + \delta_6 Urban\_Sprawl_{it} + \delta_7 Polycentric_i + D_t^{2019} + D_t^{2020} + D_t^{2021} + \varepsilon_{it} \quad \textbf{(3)}$$

Although these baseline specifications are of interest because they estimate the general role of LEZ on traffic congestion, the main goal of this paper is to estimate whether LEZs are having any differentiated impacts on traffic recovery after the shock of Covid-19. For this purpose, our main contribution comes from an alternative specification that considers different timing effects of LEZs, taking 2021 as the first year of the pandemic recovery (*PostCovid*). Equation 4 details the specification that allows us to evaluate the effect of LEZs on congestion in 2021.

$$\log(Congestion)_{it} = \alpha + \beta_1 D_{it}^{LEZ\_2018-2020} + \beta_2 D_{it}^{LEZ\_POSTCOVID} + \gamma D_{it}^{LTZ} + \delta_1 \log(Rail)_{it} + \delta_2 Metro_{it} + \delta_3 \log(Motorization)_{it} + \delta_4 \log(Population)_{it} + \delta_5 \log(GDP)_{it} + \delta_6 Urban\_Sprawl_{it} + \delta_7 Polycentric_i + D_t^{2019} + D_t^{2020} + D_t^{2021} + \varepsilon_{it} \quad \textbf{(4)}$$

where $D^{LEZ\_2018\text{-}2020}$ accounts for cities with LEZs in years 2018, 2019 and 2020 and $D^{LEZ\_POSTCOVID}$ accounts for cities with LEZs in the year 2021. Hence, these variables are the interaction between a dummy variable for LEZ and two dummy variables that differentiate between 2018-2020 and the post-Covid year that is 2021. It should be noted that most cities with LEZs kept the regulations in place throughout the whole period 2018-2021. Thus, these binary variables are capturing time differences for cities with LEZs rather than variations in traffic regulations over time.

Results

Our estimates on the baseline specification using pooled data models are displayed in Table 3.[3] Columns 1 and 2 display results for equation (1) presented above. Column 3 displays results for equation (2), considering the territorial scope of LEZs**.** Column 4 shows the results for equation (3) considering the year of LEZ implementation.

Overall, the fit of our models is correct. All models show a good fit (R^2>0.50) and the joint significance test validates the explanatory power of our specification. In all cases, LEZs have

[3] Unfortunately, our final sample for the analysis loses 143 observations due to missing information, particularly regarding population and the motorization variables. Results without these variables are available upon reasonable request. They do not change our main conclusions with respect to the support for the hypothesis tested in this research.

associated coefficients that are statistically significant at the 5% or 10% level with a negative sign. This indicates that cities with LEZs suffer lower congestion levels than the cities without this traffic restriction. Note that this is an average correlation for all four years in our sample. Our results suggest that the average reduction in the congestion level achieved by LEZs is about 8.5%. Considering the average congestion level of 24% of our sample, this implies a reduction of 2 percentage points. The territorial scope of LEZs does not seem to significantly affect their effect according to the estimates displayed in column 3. Coefficients are both statistically significant at the 10% level, and coefficients are quite close, although it is higher for the type of LEZ that is constrained to the core city. The coefficients (and statistical significance) of the two LEZ variables that differentiate between the period of implementation shows that the impact of LEZs is clearly higher for the old LEZ cities.

Other restrictions, such as limited traffic zones, do not seem to produce congestion relief because the coefficient is not statistically significant. In addition, the magnitude of its effect is half the effect produced by LEZs.

Regarding our control variables, public and private transportation variables are statistically significant and display the expected sign. Public transportation supply diminishes congestion, while motorization increases it. Population is also positively associated with congestion, but GDP per capita shows a negative correlation. This means that the effect produced by better transportation infrastructure and systems linked to income is the force driving this result, rather than the usual higher mobility demand of higher income groups.

Urban form also seems to matter. Both the ratio of the functional area over the core city area and the polycentric feature of a city are negatively associated with congestion and highly statistically significant at 1%, as expected.

Table 3. Pooled data OLS model estimates on the logarithm of congestion.

Covariates	Pooled OLS (1)	Pooled OLS (2)	Pooled OLS (3)
LEZ	-0.0851*		
	(0.0443)		
Wide LEZ		-0.0684*	
		(0.0397)	
Central LEZ		-0.0867*	
		(0.0479)	
New LEZ			-0.0525
			(0.0619)
Old LEZ			-0.114**
			(0.0501)
Rail	-0.191**	-0.188**	-0.199***
	(0.0737)	(0.0739)	(0.0739)
Metro	-0.0183***	-0.0184***	-0.0178***
	(0.00695)	(0.00694)	(0.00675)
log(GDP)	-0.142**	-0.145***	-0.134**
	(0.0545)	(0.0539)	(0.0546)
log(population)	0.336***	0.335***	0.338***
	(0.0313)	(0.0316)	(0.0317)
log(motorization)	0.294***	0.294***	0.306***
	(0.109)	(0.109)	(0.110)
LTZ	-0.0427	-0.0458	-0.0519
	(0.0486)	(0.0479)	(0.0496)
Polycentric	-0.184***	-0.183***	-0.183***
	(0.0589)	(0.0599)	(0.0593)
Urban sprawl	-0.0388***	-0.0385***	-0.0395***
	(0.00555)	(0.00563)	(0.00573)
Constant	0.723	0.764	0.551
	(0.943)	(0.941)	(0.950)
Observations	433	433	433
R-squared	0.544	0.544	0.547
Year FE	YES	YES	YES
Clusters	City	City	City

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%. Standard errors in parentheses

Table 4 displays our key selected results on the differentiated role of LEZs before and after Covid-19. All estimations include all covariates and year-specific and country-specific fixed effects, except the Fixed Effects Model that considers city-specific fixed effects instead of country-specific fixed effects. Column 4 again displays the Pooled OLS model, while models 5-7 consider Panel Data methods. Consistently, our results indicate that LEZs are only contributing to congestion relief in the post-Covid year (2021), while it was not statistically significant in the previous years (2018-2020). Only very slight differences exist between the Population Averaged

Model (GEE), Random Effects Model (RE) and Fixed Effects Model (FE). Coefficients associated to LEZs in the post-Covid year are always negative and statistically significant at 1% across models. Thus, estimates seem to confirm our main hypothesis, which suggests that cities with LEZs experienced slower recoveries of traffic after Covid than cities without these traffic restrictions. Moreover, in terms of the magnitude of effects, coefficient size also suggests an average reduction in congestion of between 5.2% and 5.6%, depending on the model. For the average congestion of our sample, this implies a reduction of 1.3 percentage points.

Regarding the control variables, the sign and statistical significance of the variables of rail, population, urban sprawl and (mostly) polycentric are like those obtained in regressions reported in table 3. The rest of variables loses its statistical significance, while the sign of the variable LTZ turns out positive. Note that the effect of these variables may be captured by the inclusion of country or city specific effects. In this regard, note that the city fixed effects model captures the effect of time-invariant variables (rail, metro, polycentric, urban sprawl).

Table 4. Pooled and Panel Data estimates on the logarithm of congestion, by period.

Covariates	Pooled OLS (4)	Panel GEE (5)	Panel RE (6)	Panel FE (7)
LEZ				
LEZ_2018-2020	-0.0159	0.0162	0.0170	0.0208
	(0.0421)	(0.0200)	(0.0208)	(0.0210)
LEZ-PostCovid	-0.0952**	-0.0564***	-0.0555***	-0.0522**
	(0.0412)	(0.0197)	(0.0206)	(0.0206)
Rail	-0.164***	-0.152***	-0.152***	
	(0.0599)	(0.0404)	(0.0412)	
Metro	-0.00829	-0.00671	-0.00668	
	(0.00656)	(0.00643)	(0.00671)	
log(GDP)	-0.0412	-0.0426	-0.0445	-0.110
	(0.197)	(0.184)	(0.191)	(0.181)
log(population)	0.244***	0.224***	0.224***	0.205***
	(0.0279)	(0.0262)	(0.0274)	(0.0137)
log(motorization)	-0.0296	0.0951	0.116	0.708
	(0.126)	(0.104)	(0.112)	(0.441)
LTZ	0.0821	0.0938**	0.0974**	0.134***
	(0.0541)	(0.0408)	(0.0403)	(0.0159)
Polycentric	-0.0714	-0.0784*	-0.0786*	
	(0.0437)	(0.0444)	(0.0464)	
Urban sprawl	-0.0274***	-0.0262***	-0.0264***	
	(0.00676)	(0.00688)	(0.00719)	
Constant	2.227	1.642	1.542	-0.186
	(2.213)	(2.048)	(2.124)	(2.752)
Observations	433	433	433	433
R-squared	0.758		0.75	0.62
Wald Chi^2		897.96***		
Year FE	YES	YES	YES	YES
Country FE	YES	YES	YES	NO
Clusters	City	No	City	City
Number of cities	126	126	126	126

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%. Standard errors in parentheses. The Stata command for Generalized Estimating Equations does not allow to apply clusters.

Mechanisms

In this section, we analyse the factors that may explain our main result. LEZs reduce congestion after the pandemic but not before.

LEZ cities may differ in some key characteristics in comparison to non-LEZ cities. Table 5 provides the t tests on equal means for all variables considered in previous regressions. On the one hand, LEZ cities are richer and have a higher supply of rail infrastructures. Furthermore, they apply more often another traffic restrictions. On the other hand, they are much bigger. Even though there are differences between LEZ and non-LEZ cities in these key characteristics, this does not explain why we find differences in congestion after the pandemic but not before. Note also that our regressions already control for such differences. Similar, it could also be argued that LEZs are usually part of a bunch of measures improving public transport supply (although this is more clearly the case with congestion tolls that imply the generation of revenues for governments). Again, this would not explain why LEZ cities have a congestion-reduction effect after the pandemic but not before. Note also that our fixed effects regression control for time invariant unobservable factors and we expect modest changes in public transport supply in the short four-years period that we consider (with two of the years affected by the pandemic).

Table 5. Tests of equality means

Variables	Mean (LEZ)	Obs (LEZ)	Mean (No LEZ)	Obs. (No LEZ)	T-test
Congestion	23.33	169	24.27	411	1.33
Rail	0.285	169	0.192	411	-2.70***
LTZ	0.36	169	0.22	411	-3.46***
Metro	4.22	169	1.04	411	-11.79***
Motorization	563	161	553	337	-1.15
Population	2212	153	1132	374	-7.36***
GDP	37139	169	32049	411	-5.26***
Urban sprawl	1.73	153	1.96	374	1.20
Polycentric	0.29	169	0.11	411	-5.25***
Deaths per 100,000 (2021)	235	169	263	411	3.18***
Vaccination rate per 100 (2021)	80.19	169	77.74	411	-1.41
Stringency index (2021)	56.15	169	52.11	411	-3.88***

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%.

LEZs cities could be those that were experiencing lower traffic demand in 2021 –and therefore congestion recovery– due to Covid-19 lasting impacts. This would be the case if cities with LEZs had been particularly and relatively more hit by the virus –with higher death rates and higher mobility restrictions- during the pandemic– than the group of cities without LEZs. Furthermore, one aspect that allowed us to enter the new normal scenario was precisely the extension of vaccination in 2021. In this regard, it could be that LEZs had been less exposed to vaccination against Covid-19 than all other cities. Because data at local level is not available, we can only make the comparison between LEZ and non-LEZ cities employing national data as a proxy of death rates, the stringency of restrictions[4] and vaccination rates at the city level for 2021 (data are retrieved from *OxCGRT*). The results displayed at the bottom of Table 5 show that the mean of Covid-related death rates is lower for cities with LEZs than for cities without a LEZ in our sample, while we do not find statistical differences in the mean rate of vaccinations. However, LEZ cities have been affected by more mobility restrictions than non-LEZ cities. Table 6 shows the results of regressions that control for the stringency index, confirming our previous result that LEZ cities are less congested after the pandemic but not before. In any case, part of the effect attributed to LEZs measures could be related with more stringent mobility restrictions associated to the pandemic.

Table 6. Pooled and Panel Data estimates on the logarithm of congestion, by period (controlling for stringency index).

Covariates	**Pooled OLS (4)**	**Panel GEE (5)**	**Panel RE (6)**	**Panel FE (7)**
LEZ				
PreCovid	-0.069*	0.0005	0.0006	0.009
	(0.0398)	(0.0172)	(0.0213)	(0.0212)
PostCovid	-0.0992***	-0.0533***	-0.0525***	-0.0492***
	(0.0424)	(0.0195)	(0.0192)	(0.0191)
Stringency index	-0.005	-0.003***	-0.003***	-0.003***
	(0.0034)	(0.0011)	(0.0013)	(0.0012)
All Covariates	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Clusters	City	No	City	City
Country FE	Yes	Yes	Yes	Yes
N. Observations	433	433	433	433
R2	0.55	-	0.75	0.63
F-joint significance	36.31***	-	-	-
Wald Chi^2	-	917.34***	-	-

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%. Standard errors in parentheses. The Stata command for Generalized Estimating Equations does not allow to apply clusters.

[4] We use a stringency index that records the strictness of lockdown policies at country level that primarily restrict the mobility and behavior of citizens. In particular, it is a composite index taking value from 0 to 100 (where 100 is the strictest) based on the average score of nine indicators related to Covid19 containment and mitigation measures. They are school closures, workplace closures, cancellation of public events, restrictions on public gatherings, closures of public transport, stay-at-home requirements, public information campaigns, restrictions on internal movements, and international travel controls.

In addition to more stringent mobility restrictions due to the pandemic, two alternative hypotheses may explain the effectiveness of LEZs in reducing congestion after the pandemic. On the one hand, the fleet renewal process could have slowed down after the pandemic. In this regard, table A1 in the appendix show the share of cars with less than two years over total cars for the countries for which this information is available in the period 2018-2021. The numbers in this table show that the pandemics seems to have effectively slowed down the process of renewal of the car fleet although this process seems to be general in all countries.[5]

On the other hand, governments and citizens in LEZ cities may have better attitudes towards a sustainable mobility after the pandemic, for example increasing the use of public transportation and teleworking. The first hypothesis would be validated if the cities with the most recent LEZs are the ones that are less congested after the pandemic. The impact of the LEZs in terms of fleet renewal in cities that applied the measure many years ago would have to have occurred before the pandemic. In contrast, the second hypothesis would be validated if it is the pioneering LEZ cities that are less congested after the pandemic, assuming that the early implementation of LEZ is a proxy of better attitudes towards a sustainable mobility that could have gained more relevance after the pandemic.

Table 7 replicates the previous analyses but distinguishing between new and old LEZ cities. Results of these additional regressions provide clear evidence that cities with early implementation of LEZ are the ones that are less congested after the pandemic. This result implies that the negative impact of LEZs on congestion is not explained by a slowdown in fleet renewal but by unobservable factors such as better attitudes towards sustainable mobility that could have gained more relevance after the pandemics.

To this point, note that cities impose different requirements in terms of standards (being usually stricter for diesel cars) and the stringency in such standards could be related with the timing of the LEZ implementation. Germany can be taken as reference because it is the country

[5] Unfortunately, data of auto sales at the city level are not available.

with more LEZs in our sample and all of them can be categorized as old in our terms, except Hamburg. Most of German cities have the following emission standards: Euro 4 for diesel cars and Euro 1 for gasoline cars.[6] The rest of cities in our sample has similar standards, albeit in some cases could be slightly more or less stringent. The standards are only clearly less stringent in Naples, Rotterdam, and Utrecht because they do not apply to gasoline cars and only Rotterdam is categorized as new LEZ. Thus, we do not expect that differences in the stringency of the standards significantly influence our results.

Table 7. Pooled and Panel Data estimates on the logarithm of congestion, by period (controlling for stringency index, lez new and lez old).

Covariates	Pooled OLS (4)	Panel GEE (5)	Panel RE (6)	Panel FE (7)
LEZ				
PreCovid	-0.069*	0.006	0.007	0.010
	(0.0393)	(0.0167)	(0.0207)	(0.0205)
PostCovid_new	-0.0376	-0.008	-0.007	-0.0006
	(0.0505)	(0.0242)	(0.0192)	(0.0196)
PostCovid_old	-0.1419***	-0.0909***	-0.0899***	-0.0878***
	(0.0504)	(0.0232)	(0.0269)	(0.0257)
Stringency index	-0.005***	-0.002***	-0.002**	-0.003***
	(0.0034)	(0.0011)	(0.0013)	(0.0012)
All Covariates	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Clusters	City	No	City	City
Country FE	Yes	Yes	Yes	No
N. Observations	433	433	433	433
R2	0.55	-	0.75	0.64
F-joint significance	33.99***	-	-	-
Wald Chi^2	-	940.03***	-	-

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%. Standard errors in parentheses. The Stata command for Generalized Estimating Equations does not allow to apply clusters.

[6] The European emission standards are vehicle emission standards for pollution from the use of cars sold in the European Union. The standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. The stages are typically referred to as Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6 and Euro 7.

It could also be the case that LEZs have induced a change in local attributes related to sustainable mobility. We can test such hypothesis by examining differences between LEZs promoted by local and non-local authorities.

In Europe, the first low-emission zones were introduced in Sweden in 1996 although they only applied to heavy vehicles. Over the 2000's, the number of low-emission zones increased exponentially as one of the measures to respond to the growing social concern generated by local pollution and its consequent health risks. Also note that, since 1996, the European Commission enacted a series of air quality directives that dictated the appropriate limits for air pollution in European cities. These ultimately culminated in the *2008/50/EC Directive on Ambient Air Quality and Cleaner Air for Europe*. Hence, another incentive for cities to implement a LEZ is the risk of being fined if they exceed the maximum pollution thresholds established by the European legal framework.

The national framework for LEZs usually only involve the stickers that identify the emission levels of the cars.[7] Hence, the decision to implement or not a LEZ is usually in charge of the city council. Using a similar dataset as that used in this paper, Fageda et al. (2022) analyze the factors that explain whether cities implement or not a LEZ. The main determinant in the decision to implement an LEZ is the city's income. The higher the income level, the more likely it is that the city will decide to implement it. To a lesser extent, high pollution levels (but not high congestion levels) also influence the decision. Finally, it is also remarkable that a LEZ is more likely to be implemented in those cities where the city mayor is from a left-wing party. These results suggest that LEZ may be related with local attributes related to sustainable mobility.

While most of LEZs are implemented by local authorities, we have identified combined regional schemes that apply to the North of Italia (particularly in the regions of Emilia Romagna, Lombardia, Piamonte and Veneto). Cities affected in our sample are Brescia, Bologna, Milan, Modena, Parma, Reggio Emillia, and Torino. Furthermore, there are regional schemes in Germany

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[7] Recently, France and Spain have enacted climate laws that made compulsory the implementation of LEZs in cities with more than 150,000 (in force from 2025) and 50,000 inhabitants (in force from 2023), respectively.

(particularly in the Ruhr area and Stuttgart) that affect the cities of Bochum, Essen, Dortmund, Duisburg and Stuttgart.

Considering all this, we create a new variable that makes a distinction between different types of LEZs depending on whether they are affected by a regional scheme, or the implementation has been carried out directly by the city council. Then, we interact these two variables with the dummy that identifies the effect of old LEZs cities after the covid.

Table 8 report the results of these additional regressions that shows that the coefficients of the variables capturing the effect of both types of old LEZs cities (either promoted at the regional or local level) are negative and statistically significant. Hence, old LEZs cities have less congestion after the pandemics regardless of they have been decided at the regional or local level. These results suggest that LEZs may have induced a change in local attributes related to sustainable mobility that gained more relevance after the pandemics. If LEZs have induced a change in local attributes, we should expect significant effects regardless of the measure was initially set at the regional or local level. Even if LEZ was initially set at regional level, given that it has changed local attributes, it should have a significant negative impact on congestion as we find.

The estimated impact for LEZs that are decided at the regional level is larger than at the local level. Regional LEZs may have larger or smaller effects than local LEZs. Indeed, it is not clear a priori if the effect will be larger or not because this will depend on the specific characteristics of the implementation including, among others, the level of stringency or the size of restricted area. In this regard, it is not surprising to find larger effects in regional LEZs because they are in fact more ambitious than local LEZs. For example, it can be more effective to apply a LEZ in the entire Ruhr area that just in the city of Dortmund, or in all cities in the region of Lombardia (including the surroundings of Milan) than just in the city of Milan. In fact, our results provide some evidence in favor of the latter.

Table 8. Pooled and Panel Data estimates on the logarithm of congestion, by period (controlling for stringency index, lez new, lez old_city, lez_old_regional).

Covariates	Pooled OLS (4)	Panel GEE (5)	Panel RE (6)	Panel FE (7)
LEZ				
PreCovid	-0.0709*	0.006	0.007	0.010
	(0.0394)	(0.0167)	(0.0208)	(0.0206)
PostCovid_new	-0.0387	-0.008	-0.007	-0.0006
	(0.0596)	(0.0241)	(0.0194)	(0.0196)
PostCovid_old_city	-0.109**	-0.0742***	-0.0733***	-0.0715***
	(0.0552)	(0.0250)	(0.0286)	(0.0270)
PostCovid_old_regional	-0.271***	-0.154***	-0.152***	-0.150***
	(0.0676)	(0.0422)	(0.0461)	(0.0462)
Stringency index	-0.005***	-0.002***	-0.002**	-0.003***
	(0.0050)	(0.0011)	(0.0013)	(0.0012)
All Covariates	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Clusters	City	No	City	City
Country FE	Yes	Yes	Yes	No
N. Observations	433	433	433	433
R^2	0.55	-	0.75	0.64
F-joint significance	50.26***	-	-	-
Wald Chi^2	-	947.43***	-	-

Notes: Significance levels based on p-values at *** 1%, ** 5%, * 10%. Standard errors in parentheses. The Stata command for Generalized Estimating Equations does not allow to apply clusters.

Discussion and concluding remarks

According to the evidence reported in this research, cities with LEZs are experiencing a less pronounced traffic recovery after the shock of Covid-19. Although congestion seems to be increasing everywhere, and there is evidence showing it is increasing at a higher rate than public transportation demand, its rate of increase seems lower where LEZs are in place.

LEZs aim to cause a change in the composition of traffic, expelling the most polluting vehicles, and promoting the renewal of fleets. This is consistent with the results reported in the recent literature that highlights that LEZs are more effective at reducing pollution and improving air quality than at combatting congestion (Bernardo *et al.*, 2021). However, the Covid-19 shock could have set a perfect scenario for LEZ regulations to play a dual role, now also acting against congestion recovery after Covid-19.

On the one hand, there is sufficient evidence that shows that the Covid-19 pandemic has influenced and changed consumer behaviour (see Cruz-Cardenas *et al.*, 2021 for a literature review). The automobile industry has been one of the hardest hit by Covid-19. The pandemic significantly reduced the number of sales and displaced purchasing decisions to the future due to uncertainty. No doubt, the epidemic's negative income effects reduced the purchase propensity for automobiles (Yan *et al.*, 2022). Due to the major impact on the automobile industry, the expected change in fleet composition towards a greener fleet under LEZ schemes would have been slowed down by the effects of Covid-19 on vehicle purchases. However, results of our analysis do not provide evidence in favour of the slowdown in the fleet renewal process because the cities with the most recent LEZs are not the ones that are less congested after the pandemic.

On the other hand, Covid-19 has promoted new patterns of mobility also related to the new organization of work, fundamentally the emergence of teleworking and more flexible work schedules (Albalate *et al.*, 2022), all of which reduce the in-person factor of work to some extent. Results of our analysis suggests that these new patterns of mobility that implies less travel demand may have played a more relevant role in pioneering LEZ cities. In this regard, our results suggest that LEZs may have induced a change in local attributes related to sustainable mobility that gained more relevance after the pandemics.

Our research has some limitations that must be discussed due to data availability problems. Firstly, it should be noted that we can only assess the short-term effects of Covid-19 on the effectiveness of LEZs against congestion. Our main results should be confirmed once data on more post-Covid periods are available. Secondly, we have only been able to examine the different degree in the intensity of the pandemic employing national data. Therefore, regional, and local disparities may remain. Finally, the data available for a panel of 144 cities from 25 different countries are limited. Hence, a limitation of our analysis is that we do not have data at the city level of relevant variables like public transport ridership or car sales.

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APPENDIX

Table A1. Share of cars with less than two years over total cars

Country	2018	2019	2020	2021
Austria	18%	18%	18%	16%
Belgium	17%	18%	18%	16%
Czechia	11%	12%	12%	10%
Denmark	16%	15%	15%	14%
Finland	7%	7%	7%	6%
France	16%	11%	12%	11%
Germany	20%	20%	20%	19%
Hungary	7%	8%	8%	8%
Ireland	19%	19%	19%	16%
Italy	10%	10%	10%	9%
Latvia	4%	4%	4%	4%
Netherlands	15%	15%	16%	15%
Poland	6%	6%	7%	6%
Portugal	8%	8%	8%	7%
Romania	3%	3%	4%	4%
Slovenia	8%	9%	8%	7%
Spain	9%	10%	10%	8%
Sweden	20%	19%	18%	16%

Source: Eurostat. Data for Greece, Iceland, Norway, Slovakia, Switzerland and United Kingdom are not available.