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Pollution and congestion in urban areas: The effects of low emission zones[☆]

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ABSTRACT

The great weight that the car has as a means of mobility in large cities generates significant negative externalities both in terms of pollution and congestion. The goal of this paper is to examine the effectiveness of low emission zones (LEZs) and to compare it with the existing results in literature on the effectiveness of urban tolls. First, we build up a theoretical model that departs from De Borger and Proost (2012), who study the effects of urban tolls on congestion, by incorporating pollution into the analysis and LEZs as an alternative (quantity-based) policy measure. Then we perform an econometric analysis taking advantage of a unique and extremely original panel of large European urban areas over the period 2008–2016, using data on congestion from TomTom and data on pollution (PM2.5) from environmental sciences. We conclude that LEZs can curb pollution. They are particularly effective in highly polluted cities, when they are applied to a wide area of the city, and/or when they are stringent in the type of restricted vehicles. Instead, LEZs are ineffective in mitigating congestion. This is a very relevant result, given the growing importance of LEZs in Europe.

1. Introduction

The great weight that the car has as a means of mobility in large cities generates significant negative externalities both in terms of pollution and congestion. In particular, the problem of road congestion in urban areas is explained by the fact that supply (infrastructure) is unable to absorb demand, especially during peak hours. The coexistence of a fixed supply and a variable demand entails an important dilemma: if the supply is adequate to meet the demand at peak times, there will be excess capacity during off-peak periods; but if the supply is adequate to meet demand during off-peak hours, there will be excess demand at the peak periods. The second scenario is the usual one in most large cities.

Urban congestion produces traffic jams that affect commuter drivers, but also pedestrians that find their streets blocked by an excessive number of vehicles that produce noise and pollution. In this regard, the economic costs of congestion are very high. For example, the consulting firms *INRIX* and *Centre for Economics and Business Research* carried out a study in 2013 to estimate the economic impact of the delays caused by traffic jams in the UK, France, Germany, and the US. In this study, three costs are identified: *i)* the reduction in labor productivity, *ii)* the effect on the price of goods caused by the additional transportation time, and *iii)* the derived CO_2 emissions. Altogether, these congestion costs represented \$200 billion in the four countries (around 0.8% of their joint GDP). In addition, given the observed trend, the study forecasts that this figure could reach \$300 billion by 2030.[1]

Furthermore, polluting emissions are the main cause of the death of 3.3 million people a year in the world (more than AIDS, malaria, and the flu together) and, no doubt, traffic is one of the main causes (Lelieveld et al., 2015). The World Health Organization (WHO) has a database that measures the air quality of the 3,000 most important cities in the world (with a population exceeding 100,000 inhabitants) in terms of PM10 and PM2.5 particles.[2] The WHO warns that 92% of the population lives

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[1] Information from The Economist (2014).

[2] PM10 are coarse particles with a diameter between 2.5 and 10 micrometers (μm), and PM2.5 are fine particles with a diameter of 2.5 μm or less.

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in places with a harmful air quality (2014 data) and that air pollution around the world causes 3 million premature deaths every year (2012 estimate).

The WHO has recommended the use of indicators based on PM2.5 (as opposed to those based on PM10) because PM2.5: *i)* are considered a better indicator of urban pollution due to their mainly anthropogenic origin as they come largely from diesel emissions, and *ii)* imply serious effects on human health due to their composition rich in very toxic compounds and their great capacity of penetration in the respiratory tract.[3] PM2.5 are associated with the exacerbation of respiratory alterations, such as bronchitis and cardiovascular diseases. This type of pollution from urban traffic is associated with increases in the morbidity and mortality of the exposed population and with the growing development of asthma and allergies among children. In addition, as these particles are very light, they generally remain in the air during long periods. According to the WHO Health Protection Guideline Values, an average annual concentration of 10 $\mu g/m^3$ would be the lowest level for which an association between cardiopulmonary effects and mortality due to prolonged exposure to PM2.5 has been detected (this value is 20 $\mu g/m^3$ for PM10).[4]

Note also that the relationship between congestion and pollution is clear, since prolonged car circulation at reduced speeds has a notable effect on the emission of polluting substances (Barth and Boriboonsomsin, 2008; Beaudoin et al., 2015; Parry et al., 2007). The median spline estimation in Fig. 1 shows the relationship between pollution and congestion in our sample of European cities without imposing any restriction or shape on the functional form of this relationship. Data are for 2016. Although the plot in Fig. 1 displays an unclear pattern for moderate levels of congestion (up to 30% of additional travel time compared to a free flow situation), we observe that pollution increases significantly with congestion in an unambiguous way from this threshold onwards.

Investments in capacity are extremely expensive, involve long gestation periods, and are not effective in urban areas with dense road networks.[5] Therefore, two main types of measures can be applied depending on whether they are quantity- or price-based. The most popular quantity-based measure in Europe are the low emission zones (LEZs), which are widespread in the continent: they have been implemented in 41 cities from 9 countries.[6] LEZs ban polluting vehicles (i.e., those not complying with emission standards) from city centers. Thus, their primary goal is not to mitigate congestion but to reduce pollution. Price-based measures consist in charging urban tolls, typically to enter/exit to/from the city center during peak hours. Urban tolls increase drivers' travel cost and reduce traffic consequently. They have been applied in few cities, being the most important ones Singapore (1975), London (2003), Stockholm (2007), Milan (2008), Gothenburg (2013), and Palermo (2016).[7]

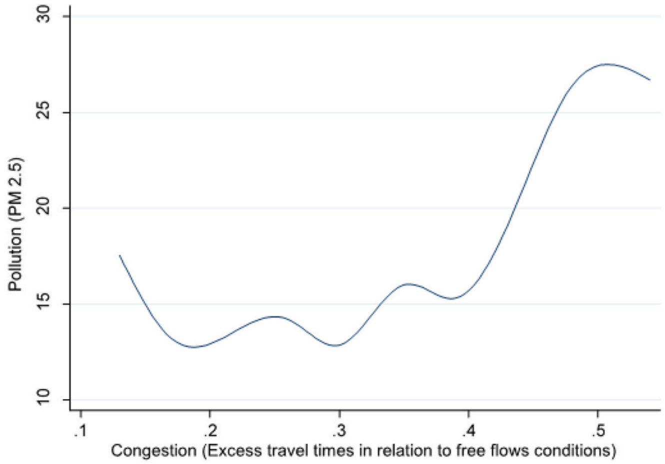

Fig. 1. Median spline between pollution and congestion for 2016.

We develop a theoretical model that compares the effectiveness and acceptability of LEZs and urban tolls to deal simultaneously with pollution and congestion, but taking clearly into account that tolls are designed to mitigate congestion while the declared goal of LEZs is to curb pollution. This is the first theoretical attempt to model LEZs. Our model departs from De Borger and Proost (2012), who study the effects of urban tolls on congestion. We extend their model by incorporating pollution into the analysis and by considering LEZs as an alternative (quantity-based) policy measure.

While our theoretical model analyzes both tolls and LEZs, our empirical analysis focuses on the effectiveness of LEZs because the impact of urban tolls on pollution and congestion cannot be evaluated in the considered period (2008–2016) as only two cities (Gothenburg in 2013 and Palermo in 2016) did implement this policy. However, we review (in Section 3) the origin of urban tolls in Europe along with the existing results in the literature on their effectiveness. This section also: *i)* helps understanding the difficulty in implementing urban tolls due to their unpopularity (along with the strategies to overcome it, being the most important ones the use of trial periods and the investment in public transit), thereby connecting with our theoretical analysis that analyzes both effectiveness and acceptability; and *ii)* makes reference to the European cities that have combined urban tolls and LEZs.

We then estimate (in Section 4) the effectiveness of LEZs by means of a city fixed effects model that identifies changes from one year to another. Since the effect of time-invariant variables cannot be captured (as they are absorbed by the city fixed effects), we measure the impact of the policies implemented after 2008. We use a unique and extremely original panel of large European urban areas over the period 2008–2016, containing data on congestion from TomTom and data on pollution (PM2.5) from environmental sciences.[8] Thus, we can exploit the existing variability among a high number of cities.

Previous studies for German cities suggest that LEZs can be effective in improving air quality. Malina and Scheffler (2015) analyze the impact of LEZs on PM10 emissions with data for the period 2000–2009, finding a reduction of 13%. Still 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 a significant impact of LEZs in reducing NO, NO_2, and NOx. The magnitude of the impact is around 4%.

Barahona et al. (2020) analyze the effects on local pollution

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[3] They are 100% breathable and travel deep into the lungs, depositing in the pulmonary alveoli and even being able to reach to the bloodstream.

[4] Logically, the risk increases with the concentration of particles. More specifically, for levels of 35 $\mu g/m^3$ of PM2.5 (or 70 $\mu g/m^3$ of PM10), WHO quantifies this increase in risk by 15% (WHO, 2005).

[5] Duranton and Turner (2011) show that new road capacity generates a proportional increase in demand so that the increased provision of roads is unlikely to relieve congestion.

[6] Another quantity-based measure is the one based on license plate numbers (even vs. odd). It has been applied in some European cities (such as Madrid or Lyon) during highly polluted periods. More systematically, it has been implemented in Latin American cities such as Buenos Aires, São Paulo or Mexico City (De Grange and Troncoso, 2011).

[7] There are other examples of urban tolls such as Durham (2002) or Valletta (2007) but they affect a few streets in the historic center of these small cities. Urban tolls are also applied in several cities in Norway but their primary purpose is to collect funds for road investments (Larsen and Østmoe, 2001).

[8] We are indebted to Aaron Van Donkelaar (Department of Physics and Atmospheric Science at Dalhousie University, Canada) for his generous collaboration by providing us with the pollution data (PM2.5) being used in this paper.

emissions achieved by vintage-specific driving restrictions that impose limits on the most polluting cars. Within these restrictions, they differentiate between those designed to work through the intensive margin (number of miles driven) and those designed to work through the extensive margin (type of car driven). An example of the former are license-plate bans that impose a uniform restriction on all cars regardless of their emission rate, such as Mexico City's *Hoy No Circula* (HNC) program that was implemented in 1989 and reformed later on to exempt new vehicles from the restriction for their first eight years. An example of the latter are the LEZs that constitute the focus of our paper. They conclude that driving restrictions perform poorly when designed to affect drivers' intensive margin (i.e., amount of travel) as they treat all cars equally, regardless of how much they pollute. Instead, restrictions concerning drivers' extensive margin that differentiate cars by their pollution rates are effective in moving the fleet composition toward lower-emitting vehicles.

Some other studies analyze 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% in terms of NO_2 and NO_x up to 10% in terms of 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 Greater London. They show that PM10 concentrations within the limits of the LEZ dropped by 2.46%–3.07% as compared to a lower decrease of 1% in limiting areas; however, no discernible differences are found for NO_x concentrations. Cesaroni et al. (2012) analyze intervention policies in Rome, including the exclusion of all cars from the historical city center and the prohibition of old diesel vehicles within the railway ring. In the intervention area, they find a PM10 and NO_2 reduction of 33% and 58%, respectively (but the results are modest city-wide). It is important to acknowledge that the latter two studies do not employ any econometric techniques allowing to control for potential confounders like weather.[9],[10]

Our empirical analysis adds to this previous literature by adopting a general multi-city approach in which we measure the effect of LEZs on both pollution and congestion using data for European cities (including LEZ and non-LEZ cities). No previous study has examined the effect of LEZs on congestion and all previous studies about the effectiveness of LEZs on pollution focus either on German cities or specific cities. Furthermore, previous studies on the impact of LEZs on pollution use PM10 or nitrogen as pollutant. Instead, we examine the impact of LEZs on PM2.5, one of the most important pollutants in terms of health damage. Furthermore, we estimate quantile regressions in which we examine the impact of LEZs across the entire distribution of the outcome variables (i.e., pollution and congestion). Finally, we examine the heterogeneous impacts of LEZs related with the dimension of the restricted area and with the stringency of the measure (i.e., the types of vehicles being banned).

Our main theoretical predictions compare the effectiveness and the acceptability of urban tolls and LEZs. Looking at the effectiveness of tolls and LEZs, we conclude that the key element is the relative severity of both externalities, where the severity of the externalities has to do with the excess traffic they generate with respect to the social optimum. When congestion is more severe than pollution, urban tolls are more effective than LEZs. Instead, LEZs are effective in curbing pollution but not in mitigating congestion, even though the same cars produce congestion and pollution simultaneously. This finding is consistent with our empirical findings.

Focusing on the acceptability of policy measures, LEZs are always more popular than tolls, irrespective of the relative severity of both externalities. Consequently, they are easier to implement by local authorities. The main reason is that remaining commuters have to pay when tolls are applied but are not affected by LEZ regulations because they own clean cars. Therefore, when LEZs are applied, they can continue driving on less congested roads (with the subsequent time saving) and take advantage of a less polluted atmosphere.

Hence, local authorities may face a tradeoff between effectiveness and acceptability when deciding between urban tolls and LEZs (or when deciding the stringency level of LEZs).

Overall, our empirical analysis provides evidence on the effectiveness of LEZs in abating pollution. LEZs are particularly effective in highly polluted cities, when they are applied to a wide area of the city, and/or when they are stringent in the type of restricted vehicles. The negative and statistically significant effect of LEZs on pollution is a remarkable result, as all cities in our sample report decreasing trends in pollution records in the considered period.

By contrast, LEZs do not seem to mitigate congestion in the streets of European cities. An explanation could come from the fact LEZs spur the renewal of the car fleet, so that older and more polluting cars are replaced by new and cleaner cars. Two additional *short-run* phenomena that can also contribute to explain this result are: *i)* the *latent demand effect*, which suggests that an initial mitigation of congestion yielding a higher average speed may attract new commuters that end up offsetting the initial mitigation, and *ii)* the *car substitution effect* in two-car households that start using more intensively the cleaner car complying with LEZ regulations.

Therefore, our empirical results confirm our theoretical predictions by suggesting that, when congestion is more severe than pollution (or when LEZ regulations are not stringent), LEZs are effective in curbing pollution but not in mitigating congestion.

The rest of the paper is organized as follows. Section 2 shows how urban congestion and pollution are modeled from a microeconomic viewpoint and the theoretical effects of congestion tolls and LEZs on both externalities. Section 3 summarizes the literature on the effectiveness of urban tolls while Section 4 presents our main empirical analysis on the effectiveness of LEZs. Finally, Section 5 offers some final considerations.

2. A model to explain the effect of urban tolls and LEZs

In this section, we first provide a welfare analysis explaining the excess traffic and the inefficiency associated with congestion and pollution. Then, using this framework, we assess the effectiveness of urban tolls and LEZs in mitigating congestion and pollution, along with some considerations on their acceptability.

2.1. The excess traffic generated by congestion and pollution

Departing from the setting in De Borger and Proost (2012), which models urban congestion to study the implementation of tolls, we incorporate pollution into the analysis and LEZs as an additional policy (besides urban tolls) to mitigate both externalities.

Car usage is the sole source of pollution in this economy.[11] Road users make at most one trip that generates congestion and pollution. The model assumes *N* potential road users uniformly distributed in terms of

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[9] The case of Milan is quite particular. A sort of low emission zone named *Ecopass* was implemented in 2008, which imposed an entrance fee to highly polluting cars. This system was transformed into an urban toll named *Area C* in 2012. The *Ecopass* reduced PM10 emissions by 18% and NO_x emissions by 17% (Rotaris et al., 2010; Anas and Lindsey, 2011).

[10] Using different frameworks, Basso et al. (2020) and Fageda et al. (2020) propose innovative formulas that combine urban tolls and vintage-specific diving restrictions. They conclude that such a hybrid system may imply significant advantages in terms of social acceptability.

[11] As it has been argued in the Introduction, cars are unambiguously the major contributor to local air pollution in European urban areas.

their willingness to pay in a decreasing way. There are two types of vehicles: clean (i.e., electric) cars and polluting cars. Each individual i has a utility given by

$$u_i = y_i + \max\{a - bi - p, 0\} \tag{1}$$

where y_i denotes consumption expenditure in other goods, p is the generalized travel cost, $a > 0$ characterizes the individual with the maximum willingness-to-pay (i.e., $i = 0$), and $a - bN = 0$ denotes the individual with the minimum willingness-to-pay (i.e., $i = N$), so that $N = a/b$. This utility function yields the aggregate inverse demand function

$$p = a - bn \tag{2}$$

with n indicating the number of drivers and $b > 0$.

Assuming the same value of time for all road users, we model the average private cost (*AC*) as

$$AC = d + \theta n \tag{3}$$

where $\theta \geq 0$ denotes congestion damage and $d \geq 0$ represents other driving costs.

We assume that polluting cars are owned by commuters with the lowest willingness to pay, so that there is a traffic threshold n_p such that $n < n_p$ is formed by clean cars and $n > n_p$ is formed by polluting cars. Although pollution is relevant from an aggregated social perspective, it is neglected by commuters who behave atomistically. Therefore, the total social cost (SC) is given by

$$SC = dn + \theta n^2 + \lambda\gamma(n - n_p) \quad \text{with} \quad \lambda = \begin{cases} 0 \text{ for } n < n_p \\ 1 \text{ for } n \geq n_p \end{cases} \tag{4}$$

where $\gamma \in (0, d)$ denotes the pollution damage caused by the fraction of polluting cars $n - n_p$ and λ is an indicator function.[12] Consequently, a totally renewed fleet of clean cars would produce no pollution at all, though the congestion externality would remain. Therefore, the marginal social cost associated to the trip (*MSC*) is

$$MSC = d + 2\theta n + \lambda\gamma \text{ with } \lambda = \begin{cases} 0 \text{ for } n < n_p \\ 1 \text{ for } n \geq n_p \end{cases} \tag{5}$$

so that the marginal pollution damage is constant and equal to γ.[13]

The analysis that follows characterizes the equilibrium and the social optimum to assess afterwards the effectiveness and acceptability of congestion tolls and LEZs.

Equilibrium and social optimum. From $p = AC$ and using (2) and (3), we obtain the number of drivers in equilibrium:

$$n^e = \frac{a - d}{b + \theta}. \tag{6}$$

From $p = MSC$ and using (2) and (5), we obtain the socially-optimal number of drivers:

$$n^* = \frac{a - d - \lambda\gamma}{b + 2\theta} \quad \text{with} \quad \lambda = \begin{cases} 0 \text{ for } n < n_p \\ 1 \text{ for } n \geq n_p \end{cases}. \tag{7}$$

where the difference $n^e - n^*$ represents the *excess traffic* observed in equilibrium, which is caused by the two existing externalities ($a > d + \gamma$ is assumed throughout the paper). Looking at the relative severity of the considered externalities, two scenarios are possible: *i)* scenario P (represented in Fig. 2), where pollution is more severe than congestion and the excess traffic is composed by the entire fleet of polluting cars, and *ii)* scenario C (represented in Fig. 3), where pollution is less severe than congestion and the excess traffic is composed by a certain combination of clean and polluting cars. Therefore the *severity* of the externalities has to do with the excess traffic they generate.

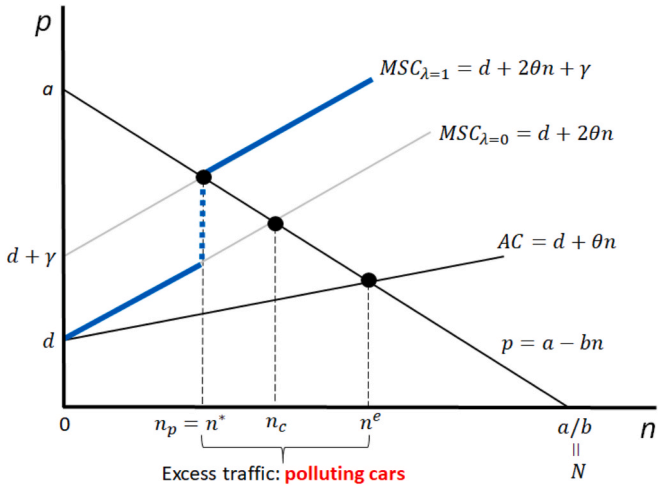

Fig. 2. Scenario P, where pollution is more severe than congestion.

LEZs and tolls have different declared policy goals, with LEZs aiming at curbing pollution (they ban polluting cars) and tolls being designed to abate congestion. However, as the cars that generate pollution do also produce congestion, the implementation of either LEZs or tolls ends up having effects on the mitigation of both externalities. The subsections that follows analyze the implementation of tolls and LEZs under the two mentioned scenarios. Interestingly, the traffic threshold n_p can be reinterpreted as the stringency of LEZs (a lower n_p meaning that larger fraction of the car fleet is deemed as polluting, therefore turning LEZs more stringent).

2.2. Scenario P: pollution is more severe than congestion

The excess traffic is composed by the entire fleet of polluting cars, so that $n_p = n^* < n_c < n^e$ (see Fig. 2). As the amount of traffic that generates pollution exceeds the one that produces congestion, the full mitigation of pollution achieved by optimal LEZs eradicates congestion but the full mitigation of congestion achieved by optimal tolls does not eradicate pollution.

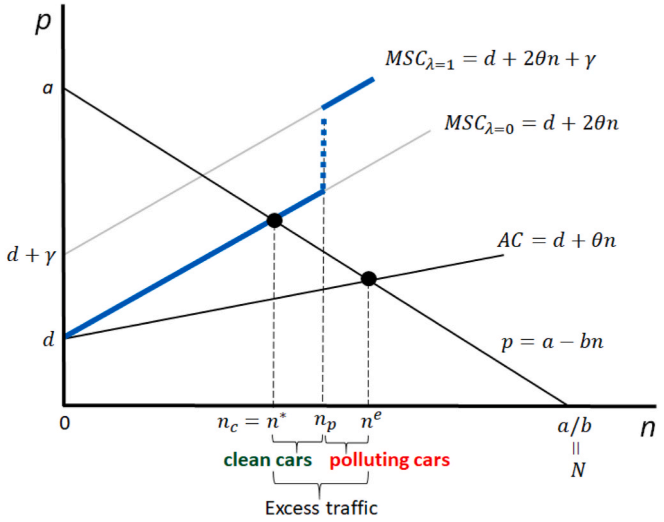

Fig. 3. Scenario C, where congestion is more severe than pollution.

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[12] The upper bound for the marginal pollution damage γ excludes the case of disproportionate environmental gains.

[13] Fageda et al. (2020) propose a related model with a marginal pollution damage that is increasing with traffic.

2.2.1. Urban tolls

Optimal urban tolls take the form of Pigouvian taxes that raise drivers' travel cost up to the level in which the excess traffic associated to congestion $\boldsymbol{n_c}$ is eliminated.

The optimal toll t_c is computed as the value of the congestion externality $MSC_{\lambda=0} - AC$ evaluated at n_c (see Fig. 2), where $n_c = (a-d)/(b+2\theta)$. Therefore,

$$t_c = \theta n_c = \theta \frac{a-d}{b+2\theta}, \tag{8}$$

which yields the toll revenues $t_c n_c = \theta (n_c)^2$ that are assumed to be equally distributed over the whole population N. With the purpose of assessing the impact of this policy over the citizens, we classify them into three groups: *non-drivers*, *remaining drivers*, and *ex-drivers*.

Non-drivers are distributed over the interval $(n^e, N]$ and do not commute neither before nor after the implementation of the toll. Therefore, they only obtain net benefits from the application of the toll in terms of distributed revenues and environmental gains.

$$\underbrace{\frac{t_c n_c}{N}}_{\text{toll revenue}} + \underbrace{\gamma \frac{n^e - n_c}{N}}_{\text{environmental gain}} > 0. \tag{9}$$

Remaining drivers are distributed over the interval $(0, n_c]$. They have a high willingness-to-pay and own clean cars. Besides receiving toll revenues and environmental gains, they also benefit from time savings related to the elimination of the excess traffic but have to pay the toll. It is easy to show that they are worse off after the implementation of the toll, i.e.,[14]

$$\underbrace{\frac{t_c n_c}{N}}_{\text{toll revenue}} + \underbrace{\gamma \frac{n^e - n_c}{N}}_{\text{environmental gain}} + \underbrace{\theta (n^e - n_c)}_{\text{time gain}} - \underbrace{t_c}_{\text{toll paid}} < 0, \tag{10}$$

Finally, *ex-drivers* are distributed over the interval $(n_c, n^e]$ and stop driving as a consequence of the implementation of the toll. Besides receiving toll revenues and environmental gains, they save the average time cost as they stop traveling but lose the value of the trip, i.e.,

$$\underbrace{\frac{t_c n_c}{N}}_{\text{toll revenue}} + \underbrace{\gamma \frac{n^e - n_c}{N}}_{\text{environmental gain}} + \underbrace{d + \theta n^e}_{\text{AC savings}} - \underbrace{(a - bn)}_{\text{value of the trip}} \lesseqgtr 0. \tag{11}$$

As indicated above, this expression can have either sign and depends on the value of n. More precisely, there is a critical value $n = \widetilde{n}$ in the segment $(n_c, n^e]$ so that *i)* the ex-drivers in $(n_c, \widetilde{n}]$ that are characterized by a relatively high willingness-to-pay end up worse off, whereas *ii)* the ex-drivers in $(\widetilde{n}, n^e]$ that are characterized by a relatively low willingness-to-pay end up better off. By equaling (11) to zero, we obtain

$$\widetilde{n} = n^e - \frac{1}{b}\left[\underbrace{\frac{t_c n_c}{N}}_{\text{toll revenue}} + \underbrace{\gamma \frac{n^e - n_c}{N}}_{\text{environmental gain}}\right], \tag{12}$$

where $\boldsymbol{n_c < \widetilde{n} < n^e}$.[15] Therefore, the proportion of ex-drivers that improve after the implementation of the toll increases with the benefit of becoming non-driver (i.e., the distributed toll revenue and the environmental gain).

Taking into account all the consumers, those located at $n < \widetilde{n}$ (remaining drivers and some ex-drivers) end up worse off whereas those located at $n > \widetilde{n}$ (some ex-drivers and non-drivers) end up better off. Therefore, the following lemma arises.

Lemma 1. *Under scenario P, comparing optimal urban tolls and the status quo (i.e., no policy), there is a majority in favor of urban tolls for $\widetilde{n} < N/2$. This support is increasing with the share of redistributed toll revenues and the environmental gain resulting from traffic reduction.*

2.2.2. LEZs

Given that the excess traffic is it composed by the entire fleet of polluting cars under scenario P, optimal LEZs fully eliminate it as $n_p = n^* < n_c < n^e$ (see Fig. 2), where $n_p = n^* = (a - d - \gamma)/(b + 2\theta)$. Therefore, they can abate congestion and pollution simultaneously. However, LEZs do not raise any revenue. Proceeding as before, we assess the effect of this policy over *non-drivers*, *remaining drivers*, and *ex-drivers*.

Non-drivers $(n^e, N]$ are not affected by the restriction and receive the benefits of breathing a cleaner air due to the achieved pollution abatement, i.e.,

$$\underbrace{\gamma \frac{n^e - n^*}{N}}_{\text{environmental gain}} > 0. \tag{13}$$

Remaining drivers $(0, n^*]$ own clean cars and are not affected by LEZ regulations. They can continue driving on less congested roads (with the subsequent time saving) and take advantage of a less polluted atmosphere, i.e.,

$$\underbrace{\gamma \frac{n^e - n^*}{N}}_{\text{environmental gain}} + \underbrace{\theta (n^e - n^*)}_{\text{time gain}} > 0. \tag{14}$$

Finally, *ex-drivers* $(n^*, n^e]$ lose the value of the trip but take advantage of environmental gains and AC savings, i.e.,

$$\underbrace{\gamma \frac{n^e - n^*}{N}}_{\text{environmental gain}} + \underbrace{d + \theta n^e}_{\text{AC savings}} - \underbrace{(a - bn)}_{\text{value of the trip}} \lesseqgtr 0, \tag{15}$$

and can end up better or worse off depending on their willingness-to-pay. The cutoff value that equals (15) to 0 is now

$$\check{n} = n^e - \frac{1}{b} \underbrace{\gamma \frac{n^e - n^*}{N}}_{\text{environmental gain}}, \tag{16}$$

where $\boldsymbol{n^* < \check{n} < n^e}$.[16] Ex-drivers in $(n^*, \check{n}]$ are harmed by the policy while those in $(\check{n}, n^e]$ are benefited.

Looking at the effects of LEZs as compared to those of urban tolls, the most salient difference is found on the fact that remaining divers are now better off, as shown in Fig. 4. Consequently, the following result arises.

Lemma 2. *Under scenario P, comparing optimal LEZs and the status quo (i.e., no policy), there is a majority in favor of LEZs for $\check{n} - n^* < N/2$. This support is increasing with the environmental gain resulting from traffic reduction.*

Looking at Lemmas 1-2, we can conclude that LEZs are more effective and easier to implement than tolls as they would receive a larger social support, i.e., $\widetilde{n} > \check{n} - n^*$.[17]

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[14] Using (6)-(8), and $N = a/b$, then the expression in (10) becomes $-\frac{b\theta(a-d)[b(d-\gamma)+\theta(a+d-2\gamma)]}{a(b+\theta)(b+2\theta)^2}$, which is negative for $\gamma < d$.

[15] First, $\widetilde{n} < n^e$ is observed directly from the inspection of (12). Second, $\widetilde{n} > n_c$ because $\widetilde{n} - n_c = \frac{\theta(a-d)[b(d-\gamma)+\theta(a+d-2\gamma)]}{a(b+\theta)(b+2\theta)^2}$, which is positive for $\gamma < d$.

[16] First, $\check{n} < n^e$ is observed directly from the inspection of (16). Second, $\check{n} > n^*$ because $\check{n} - n^* = \frac{(a-\gamma)[b\gamma+\theta(a-d+\gamma)]}{a(b+\theta)(b+2\theta)} > 0$.

[17] $\widetilde{n} - \check{n} + n^* = \frac{a^2(b+\theta)-a[b(d+\gamma)+2\gamma\theta]+\gamma^2(b+2\theta)-\theta d^2}{a(b+2\theta)^2}$. The sign of this expression depends on its numerator, which is decreasing in γ. Hence, recalling that $\gamma < d$, the numerator will always be positive if it is positive evaluated at $\gamma = d$. For $\gamma = d$, the value of the numerator is $(a-d)^2(b+\theta) > 0$, proving consequently that $\widetilde{n} - \check{n} + n^* > 0$.

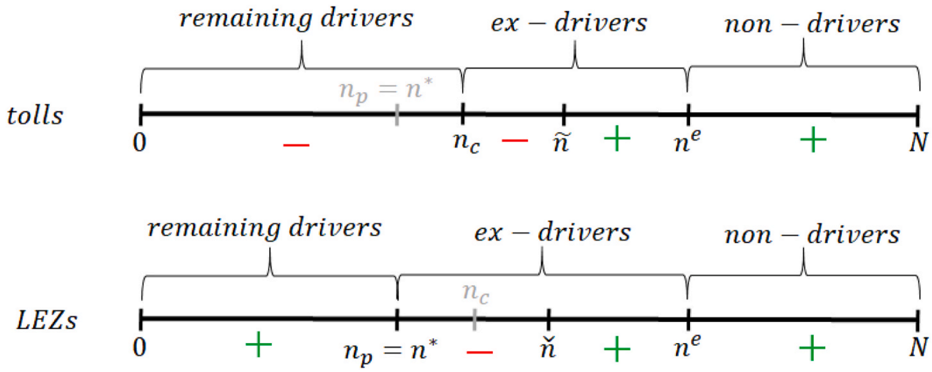

Fig. 4. Acceptability of tolls and LEZs under scenario P.

Proposition 1. *Under scenario P, LEZs are more effective than tolls as they fully mitigate both externalities simultaneously. In addition, they would receive a larger social support than tolls as* $\tilde{n} > \check{n} - n^*$.

Looking at the effectiveness of tolls and LEZs, we conclude that the key element is the relative severity of both externalities. As the same cars produce congestion and pollution simultaneously, the social optimum is determined by the more severe externality, i.e., $n^* = min\{n_c, n_p\}$, with scenario P capturing the case $n^* = n_p$ where pollution is more severe than congestion. Consequently, LEZs are more effective than tolls because their primary goal is to curb pollution.

In addition, focusing on the social support received by these two alternative policies, the above proposition highlights that the number of commuters harmed by the implementation of urban tolls ($\tilde{n}$) exceeds the number of commuters harmed by the implementation of LEZs ($\check{n} - n^*$). The main reason is that remaining commuters are benefited by LEZs while they are damaged by urban tolls.

2.3. *Scenario C: congestion is more severe than pollution*

In this case, the excess traffic is composed by a certain combination of clean and polluting cars, so that $n_c = n^* < n_p < n^e$ (see Fig. 3). As the amount of traffic that generates congestion exceeds the one that produces pollution, the full mitigation of congestion achieved by optimal tolls eradicates pollution but the full mitigation of pollution achieved by LEZs does not eradicate congestion. Independently of the applied measure, the environmental gain is logically given by $\gamma(n^e - n_p)/N$.

2.3.1. *Urban tolls*

The analysis on the effect of tolls on *non-drivers*, *remaining drivers*, and *ex-drivers* is identical to the one carried out under scenario P after replacing $\boldsymbol{n_c}$ by $\boldsymbol{n^*}$ with $\boldsymbol{n_c} = \boldsymbol{n^*} = (\boldsymbol{a} - \boldsymbol{d})/(\boldsymbol{b} + 2\boldsymbol{\theta})$, except in the term that accounts for the environmental gain (as mentioned above).

Non-drivers $(n^e, N]$ are not affected by the restriction and receive toll revenues and environmental gains, i.e.,

$$\underbrace{\frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} + > 0. \tag{17}$$

Remaining drivers $(0, n^*]$ are worse off as they have to pay the toll, even though they gain environmental and time gains along with distributed toll revenues,[18] i.e.,

$$\underbrace{\frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} + \underbrace{\theta(n^e - n^*)}_{time\ gain} - \underbrace{t^*}_{toll\ paid} < 0. \tag{18}$$

Finally, *ex-drivers* $(n^*, n^e]$ are either benefited or harmed by the toll depending on their willingness-to-pay, i.e.,

$$\underbrace{\frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} + \underbrace{d + \theta n^e}_{AC\ savings} - \underbrace{(a - bn)}_{value\ of\ the\ trip} \lesseqgtr 0, \tag{19}$$

so that the cutoff value that equals (19) to 0 is now

$$\tilde{n}' = n^e - \frac{1}{b}\left[\underbrace{\frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain}\right], \tag{20}$$

where $n^* < \tilde{n}' < n^e$.[19] Therefore, ex-drivers in $(n^*, n']$ are harmed by the policy while those in $(\tilde{n}', n^e]$ are benefited. Therefore, the following lemma arises.

Lemma 3. *Under scenario C, comparing optimal urban tolls and the status quo (i.e., no policy), there is a majority in favor of urban tolls for* $\tilde{n}' < N/2$. *This support is increasing with the share of redistributed toll revenues and the environmental gain resulting from traffic reduction.*

2.3.2. *LEZs*

Under scenario C, LEZs fully mitigate pollution but do not eradicate congestion. The analysis of LEZs on the effects on the three population groups can be easily carried out.

Non-drivers $(n^e, N]$ receive environmental gains, i.e.,

$$\underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} > 0. \tag{21}$$

Remaining drivers $(0, n_p]$ are also unambiguously better off as they take advantage of environmental and time gains, i.e.,

$$\underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} + \underbrace{\theta\left(n^e - n_p\right)}_{time\ gain} > 0. \tag{22}$$

Finally, the effect on *ex-drivers* $(n_p, n^e]$ depend on their willingness-to-pay, so that

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[18] As (18) is decreasing in n_p and $n^* < n_p < n^e$, it is therefore sufficient to show that the expression is negative for $n_p = n^*$. Using (6)-(8), $N = a/b$, and $n_p = n^*$, then (18) becomes $-\frac{b\theta(a-d)[b(d-\gamma)+\theta(a+d-2\gamma)]}{a(b+\theta)(b+2\theta)^2}$, which is negative for $\gamma < d$.

[19] First, $\tilde{n}' < n^e$ is observed directly from the inspection of (20). It remains to be shown that $\tilde{n}' > n^*$. As $\tilde{n}' - n^*$ is increasing in n_p and $n^* < n_p < n^e$, it is therefore sufficient to show that $\tilde{n}' - n^* > 0$ for $n_p = n^*$. Proceeding in that way, we obtain $\tilde{n}' - n^* = \frac{\theta(a-d)[b(d-\gamma)+\theta(a+d-2\gamma)]}{a(b+\theta)(b+2\theta)^2}$, which is positive for $\gamma < d$.

$$\underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain} + \underbrace{d + \theta n^e}_{AC\ savings} - \underbrace{(a - bn)}_{value\ of\ the\ trip} \lesseqgtr 0, \tag{23}$$

which yields the cutoff

$$\breve{n}' = n^e - \frac{1}{b}\underbrace{\gamma\frac{n^e - n_p}{N}}_{environmental\ gain}, \tag{24}$$

where $n_p < \breve{n}' < n^e$.[20] Therefore ex-drivers in $(n_p, \breve{n}']$ are harmed by the policy while those in $(\breve{n}', n^e]$ are benefited.

As under scenario P, the sole population group that ends up worse off is the relatively low willingness-to-pay ex-drivers located in $(n_p, \breve{n}']$, as shown in Fig. 5. Therefore, the following lemma arises.

Lemma 4. *Under scenario C, comparing optimal LEZs and the status quo (i.e., no policy), there is a majority in favor of LEZs for* $\breve{n}' - n_p < N/2$. *This support is increasing with the environmental gain resulting from traffic reduction.*

Looking at Lemmas 3-4, we can conclude that LEZs are easier to implement than tolls as $\widetilde{n}' > \breve{n}' - n_p$.[21] However, urban tolls are more effective.

Proposition 2. *Under scenario C, tolls are more effective than LEZs as they fully mitigate both externalities simultaneously. Instead, LEZs would receive a larger social support than tolls as* $\widetilde{n}' > \breve{n}' - n_p$.

Under scenario C, congestion is more severe than pollution and, consequently, $n^* = min\{n_c, n_p\} = n_c$. In such situation, tolls are more effective than LEZs because their primary goal is to abate congestion.

However, looking at the acceptability of both measures, LEZs would receive a larger social support as they only harm the relatively low willingness-to-pay ex-drivers $\breve{n}' - n_p$ and remaining drivers end up better off. Therefore, there is a tradeoff between effectivity and acceptability.

2.4. Discussion

The two considered scenarios show that LEZs are superior to urban tolls in terms of effectiveness and acceptability under scenario P. However, a tradeoff between effectiveness and acceptability emerges under scenario C.

Reinterpreting the traffic threshold n_p as the stringency of LEZs (a lower n_p meaning more stringent LEZs), scenario P above (where $n_p = n^* < n_c$) would capture the effects of a very stringent restriction that is able to fully internalize both externalities simultaneously. As the stringency of LEZs is relaxed and n_p increases, their effectiveness is consequently reduced and they can only mitigate congestion partially.

All in all, the LEZs standard that is ultimately determined by local authorities (n_p) takes necessarily into account the social support that the new restriction is expected to obtain. Therefore, the stringency of LEZs is likely to be relaxed to enhance their acceptability.

Our empirical results, thoroughly derived in Section 4, reveal that LEZs are effective in abating pollution but not in mitigating congestion. This finding is consistent with scenario C of our theoretical model where congestion is more severe than pollution (or LEZs are not stringent) and, consequently, have very limited effects in mitigating congestion (see Proposition 2).

As mentioned above, our empirical analysis (in Section 4) focuses on the effectiveness of LEZs because the impact of urban tolls on pollution and congestion cannot be evaluated in the considered period (2008–2016) as only two cities (Gothenburg in 2013 and Palermo in 2016) did implement this policy. However, we review in the section that follows (i.e., Section 3) the origin of urban tolls in Europe along with the existing results in the literature on their effectiveness.

3. Urban tolls in European cities

This section reviews the studies that analyze the origin of urban tolls in London, Stockholm, Milan, Gothenburg, and Palermo. Then, it summarizes the main existing results in the literature on their effectiveness.

3.1. Origin of urban tolls in European cities

The description that follows shows the relevance of both pollution and congestion in the adoption of urban tolls. This descriptive analysis also: *i)* helps understanding the difficulty in implementing urban tolls due to their unpopularity (along with the strategies to overcome it, being the most important ones the use of trial periods and the investment in public transit), thereby connecting with our theoretical analysis that analyzes both effectiveness and acceptability; and *ii)* makes reference to the European cities that have combined urban tolls and LEZs.

- London. The average speed of trips across London was lower during the 1990s than at the beginning of the 20th century (when cars started to be used). Such speed in central London fell by more than 20% after the 1960s decade (Leape, 2006). An independent survey in 1999 identified public transportation and congestion as the two most serious problems for residents in London requiring action (ROCOL, 2000) and numerous studies since 1965 reported that a congestion pricing scheme in central London could ameliorate the traffic and improve the environment (Selmoune et al., 2020). Hence, congestion costs and environmental damages explain the implementation of a licensing scheme area in the city center of London in 2003. The measure was decided by the mayor Ken Livinsgton (first elected as an independent before rejoining the Labor party) who won the election with a platform including congestion pricing in its program. Additionally, a substantial investment in the bus system was approved just before the implementation of the congestion scheme with the compromise of devoting most toll revenues to fund public transit (Santos and Fraser, 2006; Albalate and Bel, 2009).
  More recently, in 2019, London implemented a LEZ. Although LEZs are generally quantity-based measures banning vehicles not meeting the local emission standards to enter to (or exit from) a restricted area in the city center, the LEZ in London is a special case because it is applied as a price-based measure. *In addition to the congestion toll*, vehicles that do not meet emission standards must pay an *additional* fee to enter to (or exit from) the restricted area.
- Stockholm. Public discussion about a congestion charging scheme had taken place in Stockholm since the 1970s. The congestion pricing initiative came about after the 2002 national elections that led to the formation of a new government by the Social Democrats party with the support of the Green Party. The new national government in cooperation with the local government in Stockholm (also ruled by the Social Democrats) promoted a seven-month trial in 2006 based on time-differentiated prices to enter into a restricted area comprising the city center. A referendum on the permanent implementation of the pricing system in Stockholm took place after the trial period was over. During the trial, an extensive monitoring and evaluation program was carried out. Many analyses based on these data sets reported substantial traffic reductions in the charged area (Eliasson, 2008). The environmental benefits associated to the trial increased the public and political acceptance of the congestion

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[20] First, $\breve{n}' < n^e$ is observed directly from the inspection of (24). Second, $\breve{n}' > n_p$ because $\breve{n}' - n_p = (n^e - n_p)\frac{(a-\gamma)}{a} > 0$.

[21] As $\widetilde{n}' - \breve{n}' + n_p = n_p - \frac{1}{b}\frac{t^* n^*}{N}$ is increasing in n_p and $n^* < n_p < n^e$, it is therefore sufficient to show that $\widetilde{n}' - \breve{n}' + n_p > 0$ for $n_p = n^*$. Proceeding in that way, we obtain $\widetilde{n}' - \breve{n}' + n_p = \frac{n^*}{a}(a - t^*) = \frac{n^*}{a}\left(\frac{ab+\theta(a+d)}{b+2\theta}\right)\rangle 0$.

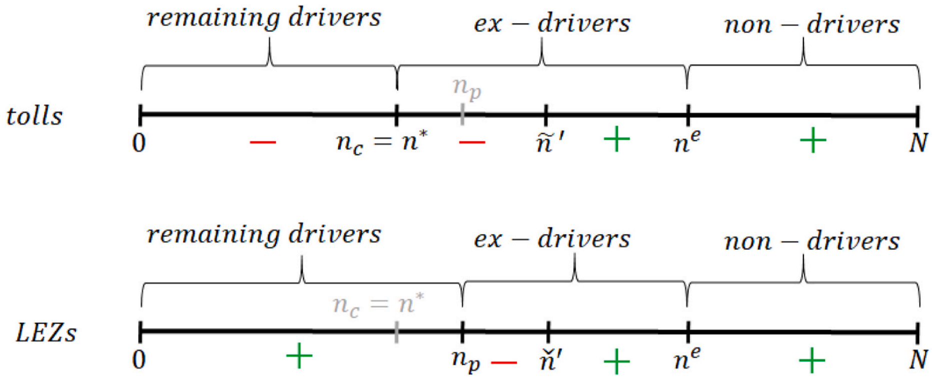

Fig. 5. Acceptability of tolls and LEZs under scenario C.

pricing scheme (Eliasson and Jonsson, 2011; Börjesson et al., 2012). The permanent urban toll was approved by a majority of voters (52% support) and, therefore, it was re-introduced in August 2007. Hårsman and Quigley (2010) examined the variability in the votes across 339 zones of the city, finding a larger support in traffic zones where average time savings implied by the toll system were higher. Kottenhoff and Brundell Freij (2009) underlined the determinant role of public transportation (in particular, the introduction of new bus lines) in the acceptability of the toll. However, the toll revenues raised when the system was reintroduced on a permanent basis (by an alliance of right-wing parties) were allocated to Stockholm's motorway ring road (Börjesson et al., 2012).

More recently, in 2020, Stockholm implemented a standard LEZ in addition to the aforementioned congestion toll.

- Milan. Milan is one of the cities with the largest number of cars per inhabitant in the world. This intensive use of private transportation together with adverse climate conditions in the region lead to very high pollution records (Rotaris et al., 2010). In fact, the city council of Milan has been applying a number of policy initiatives to curb pollution since the 1990s (Gibson and Carnovale, 2015). The mayor of the city (affiliated to the right-wing party Forza Italia) launched Ecopass in 2008, a program initially planned to last one year but finally extended until the end of 2011. It consisted in a package of policies including investments in public transportation, higher parking fees, and restrictions to enter into the city center. Such restrictions were a combination of a *pollution charge and a LEZ*: the most polluting vehicles were banned and an emission-based charging scheme was applied to the allowed vehicles. In a public consultation held on mid-2011, 79% of voters approved the continuation of Ecopass (Percoco, 2017). Therefore, it was re-established in 2012 under the name of Area C, which started as an 18-month pilot program becoming permanent in 2013. The Area C program is a combination of *congestion charge combined with a LEZ*: all vehicles meeting the emission standards must pay a fixed daily charge during office hours. The change from the *pollution charge* in Ecopass to the *congestion charge* in Area C can be explained by the fact that Ecopass had a modest effect on congestion as it promoted the purchase of less polluting vehicles.
- Gothenburg. Although Gothenburg was not particularly affected by high levels of congestion or pollution, a congestion charge scheme with time-differentiated prices was introduced on 2013 (similar to the one in Stockholm). Looking at our data for 2012, congestion in Gothenburg was 21% (being our sample mean 23%) while pollution measured as PM2.5 emissions was 5.1 μg/m^3 (being our sample mean 14.82 μg/m^3). The main purpose of the urban toll in this case was to co-fund investments in transportation infrastructures (Andersson and Nässén, 2016; Börjesson and Kristofferson, 2015). While the introduction of the congestion charge was accompanied by a significant improvement of public transportation and bike facilities, public support to the scheme was low: a consultative referendum was held in 2014 and 57% voted against. Although the scheme was launched by the local government (coalition of parties leaded by Social Democrats), all well-established parties in the city council supported the initiative. This wide political support is explained by the key role played by the urban toll in the negotiation of national funds for transportation investments. More precisely, projects benefiting from regional co-funding were prioritized and toll revenues were allocated to such co-funding.
- Palermo. The local government ruled by the right-wing party Forza Italia launched the urban toll in 2016 (similar to the one in Milan). The scheme is therefore a congestion charge combined with a LEZ: all vehicles meeting the emission standards are allowed to enter into the restricted area, paying a fixed daily charge during office hours. Congestion was severe in Palermo at the time of implementing the policy, as it was 41% in 2015 (being our sample mean 25%). Only Bucharest and Lodz registered higher levels of congestion in that year. The introduction of the urban toll was accompanied by a new tram system (with four lines and 44 stations) that improved substantially the public transportation options for residents.

3.2. Effectiveness of urban tolls in European cities

There is extensive evidence on the effectiveness of urban tolls in mitigating congestion and some evidence on their effect in curbing pollution. All the existing studies examine the *impact of urban tolls on individual cities* by comparing either traffic/congestion or pollution levels before and after their implementation. Therefore, the literature does not provide comprehensive empirical analyses obtained from multi-city samples because of the scarcity and the different nature of available data for each of the cities having implemented urban tolls.

All of the existing studies find urban tolls to be effective in abating congestion from the first year of implementation. The analyses for London and Stockholm show that tolls reduce congestion by 20–30% (Eliasson, 2008; Santos and Fraser, 2006; Börjesson et al., 2012 and 2014), while the impact is about 10–15% in Milan and Gothenburg (Andersson and Nässén, 2016; Gibson and Carnovale, 2015; Rotaris et al., 2010; Percoco, 2013).[22]

Furthermore, some studies provide evidence on the effectiveness of tolls in mitigating pollution. The reduction in pollution lies between 6% and 17% in Milan (Gibson and Carnovale, 2015) and between 5% and 15% in Stockholm (Simeonova et al., 2019).

Finally, additional positive effects associated with urban tolls have been also identified in the literature: in terms of traffic accidents in

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[22] In Singapore, their effectiveness has been shown to be even higher as compared to European cities (Phang and Toh, 1997; Willoughby, 2000; and Olszewski and Xie, 2005).

London (Green et al., 2016), and in terms of children health in Stockholm (Simeonova et al., 2019).

4. Empirical analysis on the effectiveness of LEZs

In this section, we first present the empirical equations we estimate to assess the effectiveness of LEZs on pollution (*poll*) and congestion (*cong*). Then we describe and explain the most relevant features of our dataset and, finally, we report our main findings.

4.1. Empirical equation and data

We estimate the following equations for city *i* at year *t*:

$$poll_{it} = \alpha + \beta_1 D_{it}^{LEZ} + \beta_2 rail\_ntwk_{it} + \beta_3 pop_{it} + \beta_4 dens_{it} + \beta_5 GDPpc_{it} + \beta_6 GDPpc_{it}^2 + \beta_7 CDD_{it} + \beta_8 HDD_{it} + \beta_9 rain_{it} + \delta' city + \lambda' year + \varepsilon_{it} \tag{25}$$

$$cong_{it} = \alpha + \beta_1 D_{it}^{LEZ} + \beta_2 rail\_ntwk_{it} + \beta_3 pop_{it} + \beta_4 dens_{it} + \beta_5 GDPpc_{it} + \beta_6 GDPpc_{it}^2 + \beta_7 rain_{it} + \delta' city + \lambda' year + \varepsilon_{it} \tag{26}$$

The dependent variable in (25) is pollution, which is based on annual mean estimates of PM2.5, i.e., particular matter having aerodynamic diameters smaller or equal to 2.5 μm. Our data rely on the method outlined in Van Donkelaar et al. (2019). We focus on the European subset that provides estimates between 33 and 80° North and −15 and 45° East, at 0.1 × 0.1° resolution (about 10 km × 10 km). For some urban areas, we may have more than one measurement point within the limits of the city. In those cases, we choose the measurement point closest to the city center. Figure A1 in the Appendix shows that the pollution trends in different measurement points of the same city follow identical patterns in the considered period.

PM2.5 is one of the most important pollutants because it penetrates into sensitive regions of the respiratory system and can cause or aggravate cardiovascular and lung diseases. PM2.5 emissions from road transportation come from two different sources: *i) exhaust emissions* produced primarily from the combustion of petroleum products (such as gasoline or diesel), and *ii) abrasion emissions* produced from the mechanical abrasion and corrosion of vehicle parts (such as the vehicle's tires, brakes, and clutch; the road surface wear; or the corrosion of the chassis, bodywork, and other vehicle components). Exhaust emissions are strongly related with the type of vehicle and, particularly, with its efficiency in petroleum consumption. Instead, abrasion emissions are independent of the vehicle type. According to publicly available data from the European Environmental Agency, both sources contribute similarly to the total emissions' volume caused by road transportation.

In contrast to previous studies that use detailed data for a specific city (or for few cities within a country), our empirical approach provides a more general analysis, as it is based on a sample composed by many cities from different countries for a relatively long-time period. In particular, we consider 130 cities from 19 different countries for the period 2008–2016. In addition to PM2.5, we have not found any homogeneous source providing comparable data on other pollutants for such a large sample of cities and a period of time. In any case, we consider that the analysis of the effectiveness of LEZs in reducing pollution in terms of PM2.5 is relevant because this pollutant is one of the most important ones in terms of health damage.

The dependent variable in (26) is congestion, which measures the additional travel time a vehicle needs to undertake a trip in a certain city as compared to a free-flow situation. Data have been obtained from TomTom.[23] Rather than relying on theoretical models or simulations, TomTom obtains real data from anonymous drivers' travel time from every city where it is active. Based on actual GPS-based measurements for each city, TomTom registers data from local roads, arterials, and highways. This is how the congestion index is built. First, a *baseline* of travel times is established under uncongested and free-flow conditions across each road segment in each city. Second, *actual* average travel times are calculated considering the entire year (24/7) and every vehicle in the city network.[24] Finally, the *baseline* and the *actual* travel times are compared to compute the *extra travel time*. Hence, the congestion index represents the extra travel time experienced by drivers due to traffic conditions.

Our main explanatory variable is a dummy that takes the value one from the year when general LEZs (i.e., applying to all vehicles) are implemented (so that we do not analyze truck-specific LEZs). LEZs ban polluting vehicles (i.e., those not complying with emission standards) from city centers or wider areas within a city. We use the information provided by CLARS (Charging, Low Emission Zones, other Access Regulation Schemes), a website promoted by the European Commission and built by Sadler Consultants Ltd.[25] These data are complemented with information from the 'European city ranking 2015: Best practices for clean air in urban transport',[26] the EcoRegion project,[27] and city regulations searched online.

The EU has shown a clear determination in reducing pollution in cities, especially since the transposition of the directives 1999/30/EC and 2008/50/EC.[28] This determination has been accompanied by the establishment of the 'Euro' regulatory standards for vehicles sold in EU member states.[29] In fact, the implementation of LEZs is directly linked to the 'Euro' regulatory standards.

Congestion data provides an average for the entire city whereas LEZs are applied to restricted areas within the city. Thus, it may be possible that LEZs actually reduce congestion in the restricted area while the aggregate effect for the entire city is modest. This limitation of our data is less relevant for pollution. Looking at cities for which we have data for different points, we observe that the evolution of PM2.5 records is very similar for all of them (see Figure A1 in the Appendix). In any case, such data limitation (both for congestion and pollution) should be less troublesome when LEZs are applied to a wide area of the city.

Another concern related to the implementation of LEZs is the potential *export of polluting cars* from city centers to unrestricted areas. To further study this issue, we exploit the availability of pollution data for different measurement points within the limits of certain cities. In such a way, it is possible to compare the impact of LEZs between restricted and unrestricted areas within the same city. Should such *export effect* be relevant, LEZs would even imply an increase of pollution in unrestricted areas.

In the analysis that follows, we take into account two different sources of heterogeneity in the implementation of LEZs that have to do with the size of their restricted area and with their stringency.

The restricted area of LEZs may comprise the city center, a large part of the city or even the entire city. Hence, we build two additional variables that differentiate LEZs applied to the city center and surrounding districts ($D_{city\_center}^{LEZ}$) from those applied to a wider area (D_{wide}^{LEZ}).

As for the stringency of LEZs, cities may impose different re-

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[23] https://www.tomtom.com/en_gb/trafficindex.

[24] Speed measurements are used to compute travel times on individual road segments and over the entire city network. A weight is then applied taking into account the number of measurements so that busier and more important roads in the network have a higher influence on the city's congestion level.

[25] http://urbanaccessregulations.eu.

[26] This ranking is included in the European research project 'Clean Air' and the German campaign 'Soot-free for the climate!' (http://www.sootfreecities.eu).

[27] http://www.baltic-ecoregion.eu/index.php?node_id=110.152&lang_id=1.

[28] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1999:163:0041:0060:EN:PDF and https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0050&from=EN.

[29] https://en.wikipedia.org/wiki/European_emission_standards.

quirements in terms of standards. In Germany, we can distinguish three different degrees in the stringency of LEZs (Wolff, 2014): *i)* LEZ 1: either Euro 2 or Euro 1 with particulate filter (diesel cars), *ii)* LEZ 2: either Euro 3 or Euro 2 with particulate filter (diesel cars), and *iii)* LEZ 3: either Euro 4 or Euro 3 with particulate filter (diesel cars), and Euro 1 with regulated catalytic converter or better (gasoline cars). To account for this variability, we build additional LEZ variables (named D^{LEZ1}, D^{LEZ2}, and D^{LEZ3}) thereby extending the German classification to all LEZ cities in our sample.

Furthermore, we address the aforementioned *export effect* by adding to the pollution sample all measurement points of LEZ cities, acknowledging that these measurement points may be located either inside the restricted area ($D^{LEZ}_{restricted\_area}$) or outside the restricted area ($D^{LEZ}_{unrestricted\_area}$).[30]

Newer cars are more efficient in petroleum consumption and must meet stricter emission standards. Therefore, the renewal of the car fleet in a city should have a clear direct effect in the reduction of exhaust emissions. Shifting attention to congestion, we should also expect a reduction (at least in the short run) as some banned drivers will not be able to purchase new *clean* cars complying with the LEZ requirements, even if the primary goal of LEZs is not to mitigate congestion but to reduce pollution. Congestion mitigation may also help in reducing abrasion emissions.

We take into account three different attributes of cities and their surrounding region as potential drivers of pollution and congestion: population, density, and income. Population is considered at the urban level using data from United Nations (World Urbanization prospects) and population-density at the NUTS-3 level where the urban area is located (data from Eurostat). Finally, the income of the urban area is given by the regional GDP per capita in purchasing power standards at the NUTS-2 level (data from Eurostat). We also add the squared GDP per capita to account for a potential non-linear relationship between the dependent variables and income.

The quality of public transportation networks is also taken into consideration. Since comparable data for urban buses are not available, we incorporate a comprehensive measure of the urban rail systems in terms of total distance of rail lines (in km), which includes metro, light trains, trams, and local trains (using data from the World Metro Database).[31]

In the pollution equation, we also consider two variables that account for weather effects, which measure the need for cooling and heating: the *cooling degree days* index (*CDD* variable) and the *heating degree days* index (*HDD* variable). The reason is that a relevant source of emissions has to do with electricity consumption by households, especially when it is generated from coal. Data for these two variables are provided at the NUTS-2 level (data from Eurostat).

HDD measures cold severity in a specific time period taking into consideration both *outdoor* and *average room* temperature. The calculation of *CDD* relies on the *base* temperature, defined as the lowest daily mean air temperature not leading to indoor heating. Although the value of the base temperature depends on several factors associated with the building and the surrounding environment, a general climatological approach is adopted in building this index and set it to 15°C. Denoting T^i_m the mean air temperature of day *i* (measured in °C), then the *HDD* of a certain year is given by

$$HDD = \left\{ \begin{array}{ll} \sum_{i}^{I} 18 - T^i_m & \text{for } T^i_m \le 15 \\ 0 & \text{for } T^i_m > 15 \end{array} \right\} \tag{27}$$

where *I* denotes the number of days in the considered year. For example, if the daily mean air temperature is 12°C, the value of the *HDD* index for that day is 6 (i.e., 18°C–12°C). Instead, if the daily mean air temperature is 16°C, the *HDD* index for that day is 0.

CDD measures heat severity in a specific time period taking into consideration both *outdoor* and *average room* temperature. As before, the calculation of *CDD* relies on the *base* temperature, which is now defined as the highest daily mean air temperature not leading to indoor cooling and is set to 24°C (by adopting a general climatological approach). Then the *CDD* of a certain year is given by

$$CDD = \left\{ \begin{array}{ll} 0 & \text{for } T^i_m < 24 \\ \sum_{i}^{I} T^i_m - 21 & \text{for } T^i_m \ge 24 \end{array} \right\} \tag{28}$$

For example, if the daily mean air temperature is 26°C, the value of the *CDD* index for that day is 5 (i.e., 26°C–21°C). Instead, if the daily mean air temperature is 22°C, the *CDD* index for that day is 0.

As we may expect less pollution and more congestion in rainy cities, we also consider a variable measuring the amount of precipitation in both regressions. Data is for the precipitation sum with unit 0.01 (mm) and have been obtained from the European Climate Assessment dataset website that uses the methodology developed by Klein Tank et al. (2002).[32]

We estimate a city fixed effects model that identifies changes from one year to another as it seems the most appropriate method to evaluate the effect of LEZs on pollution and congestion. Consequently, we include city and year fixed effects. The model is based on the *within* transformation of the variables as deviations from their average. Thus, the model allows comparing changes in pollution and congestion between cities having implemented LEZs and cities that have not done it. Furthermore, the city-fixed effects model controls for omitted and time-invariant variables correlated with the variables of interest. Finally, we add year dummies to control for yearly effects common to all urban areas.

4.2. *Descriptive analysis*

Our sample contains information from urban areas with a population exceeding 300,000 inhabitants over the considered period 2008–2016. This time span is determined by the availability of congestion and pollution data, which are the dependent variables in our analysis. Our sample has 1161 observations, with information for 130 cities from 19 different countries.

Table 1 shows the cities in our sample having applied LEZs in the considered period: 33 cities from 5 countries. There is a clear national influence, which can be explained by legislative measures at the country level or, alternatively, by neighboring effects across cities within the same country. Looking at the large countries in our sample, we observe that LEZs are widely implemented in Germany and Italy, while they have not been applied in any French, British or Spanish city in the considered period.

Table 2 shows the proportion of polluting cars that could be potentially affected by LEZ policies. We use two different measures: the percentage of cars older than 10 years and the proportion of diesel cars (data from Eurostat at the country level). Unfortunately, data at the regional or urban level are not available and no further distinctions within the group of cars older than 10 years can be done. However, despite these limitations, data in Table 2 provide interesting suggestions that will be helpful in the interpretation the results of our econometric analysis under the assumption that national differences in polluting vehicles are informative of city differences.

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[30] Departing from the driving restrictions imposed in Santiago (Chile), Barahona et al. (2020) provide a theoretical model that considers a polluted restricted area and a non-polluted unrestricted area.

[31] http://mic-ro.com/metro/table.html.

[32] https://www.ecad.eu.

Table 1
LEZ cities in our sample.

Country	City	Starting year, type of LEZ	Restricted area
Czech Republic	Prague	2016, **1**	city center
Germany	Berlin	2008, **1**; 2011, **2**	city center
	Bochum	2013, **1**; 2014, **2**	wide
	Bonn	2010, **1**; 2012, **2**; 2014, **3**	city center
	Bremen	2010, **1**; 2011, **2**	city center
	Cologne	2013, **2**; 2014, **3**	city center
	Dortmund	2013, **1**; 2014, **2**	wide
	Düsseldorf	2009, **1**; 2013, **2**; 2014, **3**	wide
	Duisburg	2013, **1**; 2014, **2**	wide
	Essen	2013, **1**, 2014, **2**	wide
	Frankfurt	2010, **1**; 2012, **2**	wide
	Hannover	2010, **1**	city center
	Karlsruhe	2013, **1**	city center
	Leipzig	2011, **1**	wide
	Mannheim	2013, **1**	city center
	Muenster	2010, **1**	wide
	Munich	2012, **1**	city center
	Stuttgart	2010, **1**; 2012, **2**	city center
	Wuppertal	2011, **1**; 2014, **2**	wide
Italy	Bologna	2016, **1**	city center
	Florence	2008, **1**	city center
	Genoa	2016, **1**	wide
	Milan	2008, **1**; 2012, **2**	wide
	Modena	2016, **1**	city center
	Naples	2011, **1**	wide
	Palermo	2016, **1**	city center
	Parma	2016, **1**	city center
	Reggio Emilia	2016, **1**	city center
	Rome	2011, **1**; 2013, **2**; 2016, **3**	city center
	Torino	2010, **1**; 2016, **2**	city center
The Netherlands	Rotterdam	2016, **1**	wide
	Utrecht	2015, **1**	city center
Portugal	Lisbon	2011, **1**; 2012, **2**; 2015, **3**	wide

Table 2
Percentage of polluting cars at the country level.

Country	% old cars (>10 years)	% diesel	Total cities in our sample	LEZ cities in our sample
Austria	32	57	1	0
Belgium	25	62	5	0
Czech Republic	59	34	2	1
Denmark	32	30	1	1
Germany	37	31	22	18
Ireland	19	41	1	0
Greece	n.a.	n.a.	2	0
Spain	45	56	13	0
France	32	69	17	0
Italy	40	41	19	11
Hungary	54	26	1	0
The Netherlands	39	17	5	2
Poland	72	28	10	0
Portugal	59	51	2	1
Romania	52	35	1	0
Slovakia	n.a.	n.a.	1	0
Finland	55	23	2	0
Sweden	38	27	2	0
United Kingdom	28	36	23	0

Note: Mean value for 2008–2016 for *% old cars* and mean value 2012–2016 for *% diesel*.

Most of cities with active LEZs are located in countries characterized by a relatively high proportion of old vehicles: Portugal (59%), Czech Republic (59%), Italy (40%), The Netherlands (39%) and Germany (37%). This situation suggests that pollution could be a severe externality, an observation that should make LEZs more effective.

Table 3
Median values of variables used in the empirical analysis.

Variable	All cities	LEZ cities	Non-LEZ cities
poll (PM2.5)	14.01	16.01	12.9
cong (%)	0.24	0.22	0.24
rail_ntwk (km)	0	13.4	0
pop (000)	582.86	603.68	577.50
dens (inhabitants per square km in region)	827.95	2027	601.35
GDPpc (EUR)	27,500	33,700	24,900
CDD (°C)	24.25	34.41	20.76
HDD (°C)	2633.09	2641.24	2614.29
rain (mm)	69,900	74,205	68,650

Table 3 shows the median values of the variables used in the empirical analysis. LEZ cities (i.e., cities having applied a LEZ within the considered period) are richer than non-LEZ cities. In fact, all LEZ cities have a median income higher than the median of the sample, with the exception of Palermo and Naples. Hence, it would be reasonable to expect a stronger effect of LEZs on pollution as compared to congestion, given that a certain proportion of drivers in LEZ cities may decide to renew their cars to comply with the LEZ requirements. LEZ cities are less congested but more severely polluted than non-LEZ cities. Note that we estimate quantile regressions instead of mean regressions to analyze the impact of LEZs across the entire distribution of the outcome variables (pollution and congestion).

Figs. 6 and 7 present the evolution of pollution and congestion (median levels) for three groups of cities: *i)* non-LEZ, *ii)* early LEZ adopters (LEZs applied during the subperiod 2008–2012 or before), and *iii)* late LEZ adopters (LEZs applied during the subperiod 2013–2016).

Fig. 6 shows that pollution in LEZ cities (both early and late adopters) increases in initial years (up to 2010) and declines afterwards. Instead, non-LEZ cities show a continuous pollution mitigation in the considered period. From a global perspective, pollution decays in the three groups of cities from 2011. This is not surprising as new cars are more fuel efficient. We run regressions for reduced samples to focus on LEZ cities and account for the potential distortion due to different trends (LEZ versus non-LEZ cities) in the initial years of the considered period.

In terms of congestion, Fig. 7 reveals a similar trend in the three groups of cities (linked to the evolution of the economic activity). Congestion remains stable or falls slightly during 2008–2012 while it rises during 2013–2016 (with some annual fluctuations). Looking at the whole period, there is an increase in congestion in the three groups of cities, which leads us to conclude that the evolution of pollution and

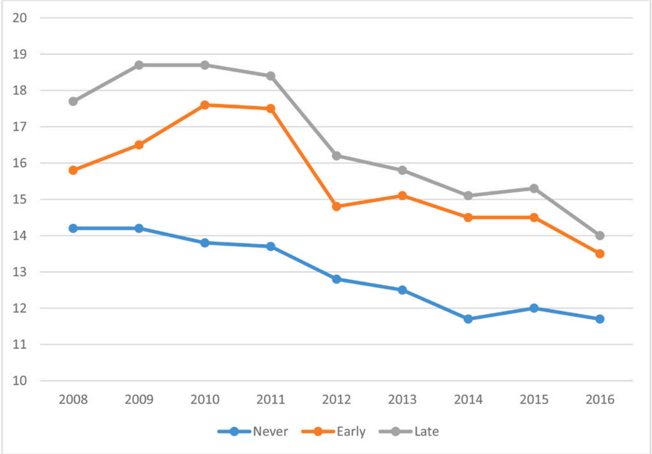

Fig. 6. Evolution of the median levels of pollution by groups of cities.
Notes. *Never*: non-LEZ cities (96 cities), *Early*: early LEZ adopters – 2008–2012 or before (19 cities), *Late*: late LEZ adopters – 2013–2016 (15 cities).

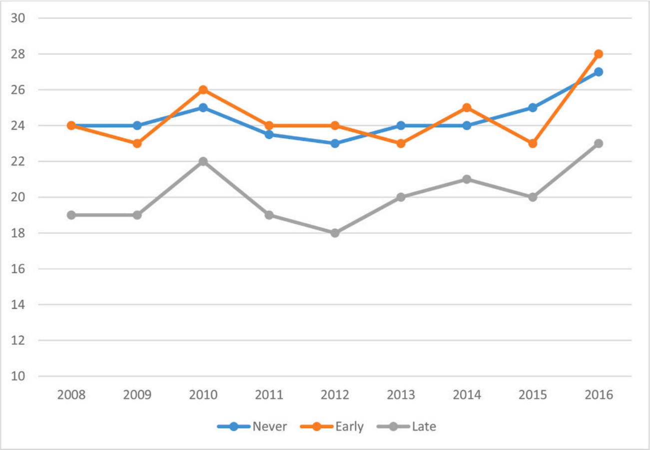

Fig. 7. Evolution of the median levels of congestion by groups of cities. Notes. *Never*: non-LEZ cities (96 cities), *Early*: early LEZ adopters – 2008–2012 or before (19 cities), *Late*: late LEZ adopters – 2013–2016 (15 cities).

congestion is really divergent. This evidence suggests that, although cars are becoming more fuel efficient, their usage is not declining over time.

4.3. Results

The classical linear model evaluates the influence of the covariates on the mean value of the dependent variable and supposes that this influence is constant in the domain of the distribution of the dependent variable. However, a constant influence is not necessarily true in our context, as LEZ policies are unlikely to be equally effective for different levels of pollution or congestion. Hence, we estimate a quantile regression model that allows the influence of covariates to depend on the quantile confidence level. Indeed, Ordinary Least Square (OLS) regressions lead to estimates of the conditional mean of the outcome variable given certain values of the covariates. By contrast, quantile regression aim at estimating either the conditional median or other quantiles of the outcome variable. While we may expect similar results for the mean and median, our expectation for low/high deciles is less clear. An additional advantage of quantile regressions relative to OLS is that estimates are more robust against outliers.

In terms of interpretation of the conditional quantiles, a result showing that LEZ policies are effective in containing pollution at higher deciles would mean that severely polluted cities become less polluted when LEZs are implemented (as compared to a scenario without LEZs).

More precisely, we run regressions conditional to all deciles from 10% to 90%, in addition to the regressions that are conditional to the median of the outcome variable (pollution or congestion).

Table 4 shows the baseline results in which the estimations are made conditional on the median of the outcome variable (pollution or congestion). Regarding the control variables, a denser rail network (*rail_ntwk*) helps in reducing congestion but not pollution. We do not find a clear impact of the population variable (*pop*), which may be explained by the fact that the sample is composed by large cities. Denser cities (*dens*) are more congested but not more polluted. Furthermore, we find a non-linear relationship between income and both outcome variables. Richer cities (*GDPpc*) are more congested and more polluted, which can be explained by the positive relationship between car trips and income. However, such relationship becomes negative for the richest cities (see coefficient of $GDPpc^2$) that are typically characterized by better vehicles and infrastructures (both roads and public transportation). The weather variables work as expected. A more intensive use of cooling (*CDD*) and heating (*HDD*) systems leads to more pollution, while rainy cities (*rain*) are more congested but less polluted (the effect on pollution is not statistically significant).

Table 4
Estimation results: Baseline.

	Dependent variable: ***poll***	Dependent variable: ***cong***
D^{LEZ}	−0.34 (0.17)**	−0.004 (0.003)
rail_ntwk	−0.006 (0.02)	−0.0004 (0.0002)**
pop	0.001 (0.001)	0.00003 (0.00002)
dens	0.0005 (0.001)	0.00002 (9.30e-06)***
GDPpc	0.0001 (0.00008)**	7.50e-06 (1.05e-06)***
$GDPpc^2$	−1.22e-09 (7.05-e10)*	−3.29e-11 (6.49e-12)***
CDD	0.009 (0.001)***	–
HDD	0.002 (0.0004)***	–
rain	−3.05e-06 (3.67e-06)	1.36e-07 (3.63e-08)***
Intercept	4.28 (6.74)	−0.13 (0.07)**
Pseudo-R^2	0.79	0.74
Obs.	1161	1161

Notes: Standard errors in parentheses and clustered at the city level. All regressions include urban area and year fixed effects. Marginal impact of LEZs on pollution:-0.025 (0.012)**. Marginal impact of LEZs on congestion:-0.018 (0.024).

More importantly, we find that LEZs are effective in abating pollution but not in mitigating congestion. The coefficient of the LEZ variable (D^{LEZ}) is negative and statistically significant at the 5% level in the pollution equation while it is negative and non-significant in the congestion equation. The marginal impact of LEZs is about −2.5% on pollution and −1.8% on congestion.

Table 5 shows the results of regressions: *i)* that account for different types of LEZs and *ii)* that distinguish between restricted and unrestricted areas within LEZ cities. For the sake of simplicity, the table just reports the marginal effect of the different LEZ variables. First, we differentiate LEZs according to the dimension of their restricted area ($D^{LEZ}_{city\_center}$ and D^{LEZ}_{wide}). Second, we classify them in terms of their stringency (D^{LEZ1}, D^{LEZ2}, and D^{LEZ3}). We also combine both criteria through the following variables: $D^{LEZ1}_{city\_center}$, $D^{LEZ2+LEZ3}_{city\_center}$, D^{LEZ1}_{wide}, $D^{LEZ2+LEZ3}_{wide}$, where LEZ 2 and LEZ 3 are merged to avoid having too small groups of cities. Finally, we distinguish between restricted ($D^{LEZ}_{restricted\_area}$) and unrestricted areas ($D^{LEZ}_{unrestricted\_area}$) within LEZ cities.

We find that LEZs are effective in curbing pollution when the restricted area is wide (the marginal impact of D^{LEZ}_{wide} is −3.2%) and when they are stringent (the marginal impact of D^{LEZ3} is −8.5%). Consistently, LEZs are also effective in wide areas when they are sufficiently stringent (the marginal impact of $D^{LEZ2+LEZ3}_{wide}$ is −4.8%). In addition, the impact of LEZs on pollution is stronger inside the restricted area (the marginal impact of $D^{LEZ}_{restricted\_area}$ is −3.2% and it is statistically significant at the 1% level) than outside the restricted area (the marginal impact of $D^{LEZ}_{unrestricted\_area}$ is −1.8% and it is statistically significant at the 10% level). Therefore, the potential diversion of vehicles to unrestricted areas does not lead to increased pollution in such areas. Instead, unrestricted areas take advantage, at least partially, from the lower emissions achieved by LEZ regulations. This is consistent with the findings of Wolff (2014).

By contrast, LEZs are ineffective in mitigating congestion regardless of the type of LEZs being considered. Therefore, LEZs are unable to reduce congestion even when they are applied to a wide area of the city. Therefore, having congestion data at the city level (from TomTom) does not seem to drive the non-significant impact of LEZs on congestion.

By considering a subsample exclusively composed of LEZ cities, we carry out the following robustness check. We run an additional regression where we focus on early LEZ adopters, so that the *treated cities* are those having applied LEZs during the subperiod 2008–2012 or before whereas the *control cities* are those having implemented LEZs during the subperiod 2013–2016. In such a way, we rule out any possible endogeneity bias related to the application of LEZs (as all cities in this subsample have applied them), thus restricting potential endogeneity

Table 5
Estimation results: Marginal impact of different types of LEZs.

	Dependent variable: ***poll***				Dependent variable: ***cong***		
	(1)	(2)	(3)	(4)	(1)	(2)	(3)
D^{LEZ}_{wide}	−0.032 (0.016)**	–	–	–	−0.021 (0.017)	–	–
$D^{LEZ}_{city\_center}$	−0.017 (0.023)	–	–	–	−0.011 (0.024)	–	–
D^{LEZ1}	–	−0.023 (0.013)*	–	–	–	−0.016 (0.016)	–
D^{LEZ2}	–	−0.019 (0.018)	–	–	–	−0.023 (0.020)	–
D^{LEZ3}	–	−0.085 (0.041)**	–	–	–	0.025 (0.031)	–
$D^{LEZ2+LEZ3}_{wide}$	–	–	−0.048 (0.020)***	–	–	–	−0.021 (0.022)
D^{LEZ1}_{wide}	–	–	−0.027 (0.019)	–	–	–	−0.024 (0.025))
$D^{LEZ2+LEZ3}_{city\_center}$	–	–	−0.022 (0.024)	–	–	–	−0.032 (0.028)
$D^{LEZ1}_{city\_center}$	–	–	−0.008 (0.017)	–	–	–	−0.011 (0.022)
$D^{LEZ}_{restricted\_area}$	–	–	–	−0.032 (0.011)***			
$D^{LEZ}_{unrestricted\_area}$	–	–	–	−0.018 (0.011)*			
Pseudo-R^2	0.78	0.78	0.77	0.73	0.74	0.74	0.76
Obs.	1161	1161	1161	702	1161	1161	1161

Notes: Standard errors in parentheses and clustered at the city level. All regressions include all controls, urban area and year fixed effects.

concerns to the year in which LEZs are actually applied.

Restricting our sample to LEZ cities, Table 6 shows the results of the estimation of the pollution and congestion equations conditional on the median of the outcome variable but focusing on early LEZ adopters (so that late LEZ adopters are considered as *control cities*).

As in the previous regression, we find a negative and statistically significant impact of LEZs on pollution (at the 1% level) and a negative but non-significant effect on congestion. The marginal impact of LEZs is −4.1% on pollution and −1% on congestion. The results of this regression suggest that a potential endogeneity bias could imply a slight underestimation of the impact of LEZs on pollution. However, it does not appear to have any effect on the non-significant impact of LEZs on congestion. The primary objective of LEZs is to abate pollution, not congestion. Thus, a potential endogeneity bias should not condition our results regarding the causal effect of LEZs on congestion.

Table 7 along with Figs. 8 and 9 show the results of the regressions for all deciles from 10% to 90% of both dependent variables. Therefore, the pollution and congestion equations are estimated conditional on the level of the outcome variable. For the sake of simplicity, we just report in Table 7 the marginal effect of the LEZ variable for each decile. We find that LEZs are effective in containing pollution when the estimation is made conditional on the median or higher deciles of the variable. In such cases, the marginal impact of LEZs ranges from −2.5% to −3% and it is statistically significant at either the 5% or the 1% level. For deciles lower than the median, LEZs are not effective in abating pollution. Hence, we can conclude that LEZs are effective in severely polluted cities. Instead, we do not find any evidence of congestion reduction associated to LEZs (considering all the congestion deciles). Thus, LEZs are ineffective in mitigating congestion, regardless of the severity of the externality.

Table 6
Estimation results: Early adopters (2008–2012) vs. late adopters (2013–2016).

	Dependent variable: ***poll***	Dependent variable: ***cong***
D^{LEZ}	−0.697 (0.26)***	−0.0003 (0.0001)
rail_ntwk	0.031 (0.10)	0.001 (0.001)
pop	0.019 (0.007)***	−0.00003 (0.0001)
dens	0.001 (0.002)	0.00005 (0.00003)
GDPpc	0.0009 (0.0004)*	0.00002 (6.34e-06)***
$GDPpc^2$	−1.13e-08 (7.45e-09)	−1.60e-10 (8.84e-11)*
CDD	0.007 (0.003)**	–
HDD	0.003 (0.001)***	–
rain	−8.37e-06 (0.00001)	−7.53e-08 (1.01e-07)
Intercept	−38.65 (15.07)***	−0.57 (0.14)***
R^2	0.78	0.84
Obs.	150	150

Notes: Standard errors in parentheses and clustered at the city level. All regressions include urban area and year fixed effects. Marginal impact of LEZs on pollution: –0.041 (0.011)***. Marginal impact of LEZs on congestion: –0.01 (0.029).

Table 7
Estimation results: Marginal impact of LEZs across different quantiles.

Quantile	Dependent variable: ***poll***			Dependent variable: ***cong***		
	Marginal impact	R^2	*Obs.*	Marginal impact	R^2	*Obs.*
0.10	0.012 (0.02)	0.77	1161	0.005 (0.007)	0.77	1161
0.20	0.017 (0.011)	0.77	1161	−0.004 (0.007)	0.75	1161
0.30	0.0027 (0.008)	0.77	1161	0.002 (0.007)	0.74	1161
0.40	−0.009 (0.014)	0.78	1161	−0.007 (0.01)	0.74	1161
0.50	−0.025 (0.012) **	0.78	1161	−0.018 (0.014)	0.74	1161
0.60	−0.030 (0.01)***	0.80	1161	−0.023 (0.014)	0.75	1161
0.70	−0.029 (0.01)***	0.81	1161	−0.004 (0.011)	0.77	1161
0.80	−0.030 (0.007) ***	0.83	1161	0.011 (0.011)	0.80	1161
0.90	−0.025 (0.011) **	0.85	1161	0.013 (0.012)	0.80	1161

Notes: Standard errors in parentheses and clustered at the city level. All regressions include all controls, urban area and year fixed effects.

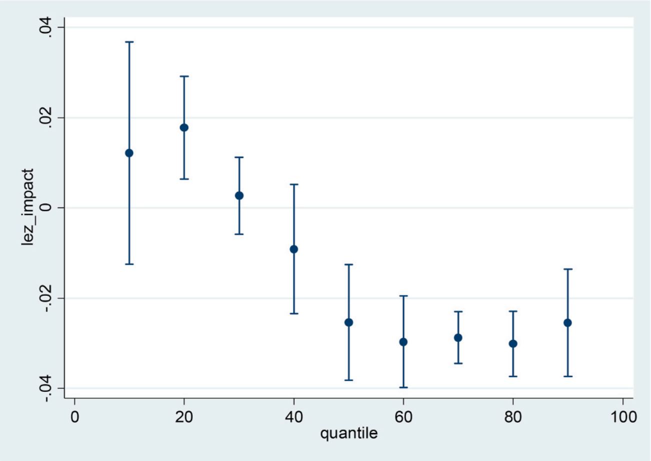

Fig. 8. Marginal impact of LEZs on pollution across quantiles.

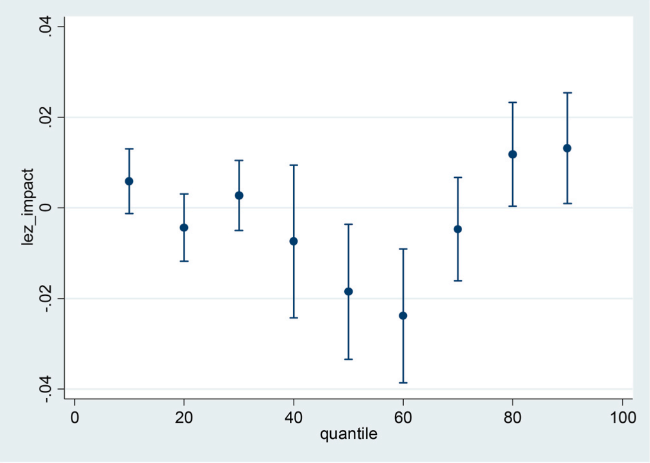

Fig. 9. Marginal impact of LEZs on congestion across quantiles.

Overall, our empirical analysis provides evidence on the effectiveness of LEZs in abating pollution. The marginal impact of LEZs on pollution ranges from −2.5% to −8.5%. Previous studies for German cities find a higher impact of LEZs on PM10 (Wolff, 2014; Malina and Scheffler, 2015) while the impact of LEZs on NO_2 is in line with our results (Morfeld et al., 2014). LEZs are particularly effective in curbing pollution when they are applied to a wide area of the city and/or when they are stringent in the type of restricted vehicles. Their impact is stronger in restricted areas as compared to unrestricted areas, but we do not find evidence of LEZs *exporting polluting cars* from city centers to unrestricted areas. Furthermore, the significant impact of LEZs on pollution is found for highly polluted cities.

Departing from the aforementioned quantile approach, Table 8 presents a timing event analysis in which we consider dummy variables for: *i)* one year before implementation, *ii)* the implementation year, and *iii)* one year after implementation. The dummy for the implementation year should capture the short-run effect of LEZs, while the dummy for one year after implementation should capture the medium-run effect. We expect LEZs to have an impact on pollution both in the short- and the medium-run. Instead, LEZs may have an impact on congestion mostly concentrated on the short-run, as the car fleet is renewed over time.

The effectiveness of LEZs in abating pollution both in the short- and the medium-run is confirmed. For the *lower deciles of the distribution*, LEZ cities were more polluted one year before the implementation that the ones in the control group (10%, 20%, 30%, 40%, and 50%). In most cases, these differences vanish during the implementation year and, in the only decile where these differences are sustained one year after implementation (20%), there is a pollution reduction as compared to the baseline situation. For the *higher deciles of the distribution* (70%, 80%, and 90%), no differences are found one year before the implementation but LEZ cities show a decrease in pollution during the implementation year and during the following year as well. Therefore, our previous result on the effectiveness of LEZs in abating pollution in severely polluted cities is confirmed.

As for the effects of LEZs on congestion, no clear pattern can be established (in line with our earlier findings). The distinction between short- and medium-run effects is particularly relevant, as different patterns between both time spans could be expected given that LEZs create incentives for car renewal over the medium run. Fig. 10 explores this issue in detail by showing the results of the timing event analysis considering three years before and three years after the implementation year. Although a theoretical short-run effect of LEZs on congestion could be expected (because car renewal requires some time), this is not confirmed empirically. LEZs have no effect on congestion neither in the implementation year nor in subsequent years. Given that LEZs have short-run effects on pollution, an explanation could be found on a rather fast car fleet renewal, at least for the considered sample of cities.

The negative and statistically significant effect of LEZs on pollution is a remarkable result, as all cities in our sample report decreasing trends in pollution records in the considered period and cars are just one of the

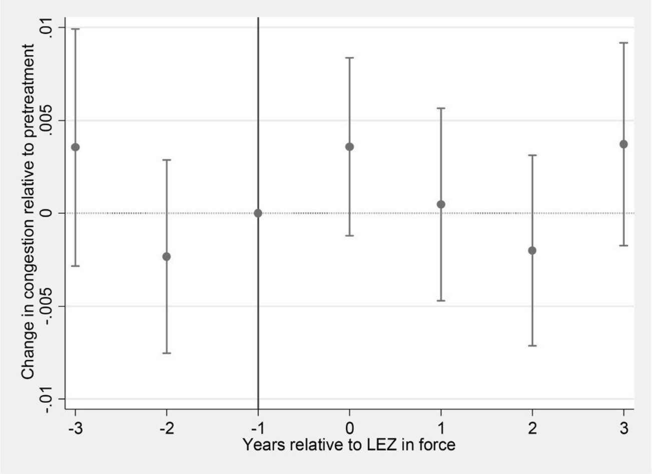

Fig. 10. Impact of LEZs on congestion over time.
Notes. Differences in the estimated coefficients relative to the year before implementation; 95
% confidence interval based on standard errors clustered at the city level.

Table 8
Estimation results: Marginal impact of LEZs across different quantiles – timing event analysis.

	Dependent variable: *poll*					Dependent variable: *cong*				
	Marginal impact one year before	**Marginal impact implementation year**	**Marginal impact one year after**	***R*²**	***Obs.***	**Marginal impact one year before**	**Marginal impact implementation year**	**Marginal impact one year after**	***R*²**	***Obs.***
0.10	0.047 (0.02)**	0.034 (0.025)	0.022 (0.021)	0.77	1161	0.018 (0.01)	0.004 (0.03)	0.0005 (0.0072)	0.77	1161
0.20	0.058 (0.01)***	0.030 (0.01)**	0.031 (0.01)**	0.77	1161	−0.008 (0.01)	−0.002 (0.01)	−0.01 (0.01)	0.75	1161
0.30	0.042 (0.01)***	0.019 (0.01)*	0.016 (0.009)	0.77	1161	−0.025 (0.009)***	−0.011 (0.013)	−0.01 (0.011)	0.74	1161
0.40	0.040 (0.02)*	0.005 (0.01)	0.003 (0.01)	0.78	1161	−0.029 (0.011)**	−0.01 (0.02)	−0.024 (0.02)	0.74	1161
0.50	0.041 (0.02)*	−0.008 (0.01)	−0.010 (0.01)	0.78	1161	−0.015 (0.03)	−0.006 (0.01)	−0.025 (0.02)	0.74	1161
0.60	0.015 (0.03)	−0.024 (0.01)	−0.017 (0.01)	0.80	1161	0.003 (0.03)	−0.004 (0.015)	−0.035 (0.018)*	0.75	1161
0.70	0.011 (0.007)	−0.019 (0.008)**	−0.019 (0.007)***	0.81	1161	0.023 (0.01)*	0.013 (0.01)	−0.005 (0.015)	0.77	1161
0.80	0.012 (0.01)	−0.031 (0.02)*	−0.026 (0.01)**	0.83	1161	0.026 (0.01)**	0.037 (0.02)**	0.023 (0.019)	0.80	1161
0.90	0.023 (0.01)	−0.033 (0.01)*	−0.032 (0.01)*	0.85	1161	0.033 (0.01)**	0.045 (0.01)***	0.033 (0.01)**	0.80	1161

Notes: Standard errors in parentheses and clustered at the city level. All regressions include all controls, urban area and year fixed effects.

sources contributing to PM2.5 emissions.

By contrast, LEZs do not seem to reduce the number of cars in the streets of European cities. An explanation could come from the fact LEZs spur the renewal of the car fleet, so that older and more polluting cars are replaced by new and cleaner cars. Two additional short-run phenomena that can also contribute to explain this result are: *i)* the *latent demand effect*, which suggests that an initial mitigation of congestion yielding a higher average speed may attract new commuters that end up offsetting the initial mitigation, and *ii)* the *car substitution effect* in two-car households that start using more intensively the cleaner car complying with LEZ regulations.[33]

Looking back to our theoretical predictions, we can conclude that scenario C (i.e., when congestion is more severe than pollution) captures the situation in the considered sample of European cities where LEZs have been implemented. Under scenario C, LEZs are effective in curbing pollution but not in mitigating congestion (see Proposition 2), a statement that is consistent with the findings obtained in our empirical exercise. As suggested above, Scenario C can also be interpreted as a situation in which the stringency of LEZs is rather low. Therefore, we could think in European local authorizes promoting and applying loose-standard LEZs with the purpose of improving their acceptability.

Other characteristics of our sample may also help explaining our results. First, as LEZs cities are relatively rich, their inhabitants may be in general financially capable of renewing their vehicles to overcome the restriction. Quite consistently, LEZs would have a significant impact on pollution but not on congestion. Second, LEZs are not necessarily accompanied by improvements of public transportation (whereas urban tolls raise revenues that are generally invested in public transit). Therefore, after the application of LEZs, commuters with a difficult access to competitive public transit will have to end up purchasing a new car, even if this acquisition represents a substantial financial effort.

Finally, it should also be acknowledge that the ineffectiveness of LEZs in mitigating congestion may also have an indirect influence on the impact of LEZs on pollution, as congestion and pollution are strongly correlated in highly congested cities (see Fig. 1). Furthermore, half of the total amount of PM2.5 are *abrasion emissions*, which are more related to the number of cars than to fuel efficiency considerations, as they are similarly generated by polluting and clean cars.

5. Conclusion and discussion

Our theoretical analysis compares the effectiveness and the acceptability of LEZs and urban tolls, which are the main quantity- and price-based restrictions being applied in European urban areas. After reviewing the literature on the origin and effectiveness of urban tolls, our empirical exercise constitutes the first attempt to examine from a broad multi-city perspective the effects of LEZs in mitigating pollution and congestion.

Overall, our empirical analysis provides evidence on the effectiveness of LEZs in abating pollution. LEZs are particularly effective in curbing pollution when they are applied to a wide area of the city and/or when they are stringent in the type of restricted vehicles. Furthermore, the significant impact of LEZs on pollution is found for highly polluted cities. Instead, we do not find any evidence of congestion reduction associated to LEZs. These empirical results are consistent with our theoretical predictions obtained when congestion is more severe than pollution.

Urban congestion tolls are applied in few cities. By contrast, LEZs are more frequently applied in European cities. As suggested in our theoretical analysis, an important explanation is found on the fact that LEZs are clearly more popular than urban tolls, which are perceived as new taxes the citizens have to pay for a service that used to be free. This reason explains the failure to apply them in cities such as Copenhagen, Edinburgh, Manchester, Helsinki, New York or Hong Kong. Some of the reasons explaining this prevalence of LEZs over tolls are that: *i)* pollution is generally perceived as a more severe externality than congestion and LEZs are perceived as more effective in curbing pollution; *ii)* LEZs affect few commuters (the owners of the most polluting cars) when their stringency level is relatively low (which is typically the case) while urban tolls affect every commuter; *iii)* urban tolls typically come together with investments in public transit to enhance their acceptability and, consequently, are more expensive to implement; *iv)* as LEZs spur the renewal of the car fleet, they are naturally aligned with the corporate interests of the vehicle manufacturing industry, an influential and strategic industry that can spend significant resources in lobbying activities which, undoubtedly, have relevant effects on policy makers and public opinion; *v)* LEZs are mostly applied in high income cities, which are characterized by a larger proportion of remaining drivers who own the less polluting cars that are not affected by LEZs and take advantage of the time and environmental gains implied by the achieved traffic reduction. Further discussion on the difference between urban tolls and LEZs in terms of acceptability can be found in Fageda et al. (2020).

A growing trend that is also observed consists in the combination of LEZs and urban tolls. For instance, London implemented in 2019 a very special a price-based LEZ in addition to the existing congestion toll. Stockholm implemented a standard LEZ in 2020 in addition to the existing congestion toll. The cases of Milan and Palermo are somewhat peculiar as well because their scheme consists in a *congestion charge combined with a LEZ*, which means that all vehicles meeting the emission standards must pay a fixed daily charge during office hours. Having both policy measures available for local authorities gives them an accrued flexibility in dealing with both externalities simultaneously, as they can either modify the level of the toll or the stringency of the LEZ, being the second option much better accepted by the population. In such situation, local authorities can deal in a better way with the tradeoff between effectiveness and acceptability when deciding the best policy mix to implement (in our theoretical model, this tradeoff arises under scenario C where tolls are more effective but more unpopular than LEZs).

Our analysis focuses mostly on short-run effects. Therefore, the ineffectiveness of LEZs in mitigating congestion even in the short-run could come from the fact LEZs spur rather fast the renewal of the car fleet. Furthermore, there are two short-run phenomena that can also contribute to explain this result are: *i)* the *latent demand effect*, which suggests that an initial mitigation of congestion yielding a higher average speed may attract new commuters that end up offsetting the initial mitigation, and *ii)* the *car substitution effect* in two-car households that start using more intensively the cleaner car complying with LEZ regulations.

Looking at long run effects, it could be argued that, once the complete car fleet becomes fully electric (thereby producing 0-emissions), vintage-specific quantity restrictions such as LEZs become ineffective turning the choice between price and quantity schemes (i.e., urban tolls versus LEZs) immaterial. However, the European Environmental Agency warns that 46% of pollutants generated by private transportation are generated by the so-called *abrasion emissions*, which are produced from the mechanical abrasion and corrosion of vehicle parts (such as the vehicle's tires, brakes, and clutch; the road surface wear; or the corrosion of the chassis, bodywork, and other vehicle components). Consequently, in this future scenario, quantity restrictions would remain effective in curbing pollution as long as they become dissociated from car vintage (because abrasion emissions are independent of vintage) and relate to other vehicle characteristics such as weight or size.

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[33] De Borger et al. (2016) study the *car substitution effect* in two-car households in response to higher fuel prices, so that one car becomes relatively cheaper.

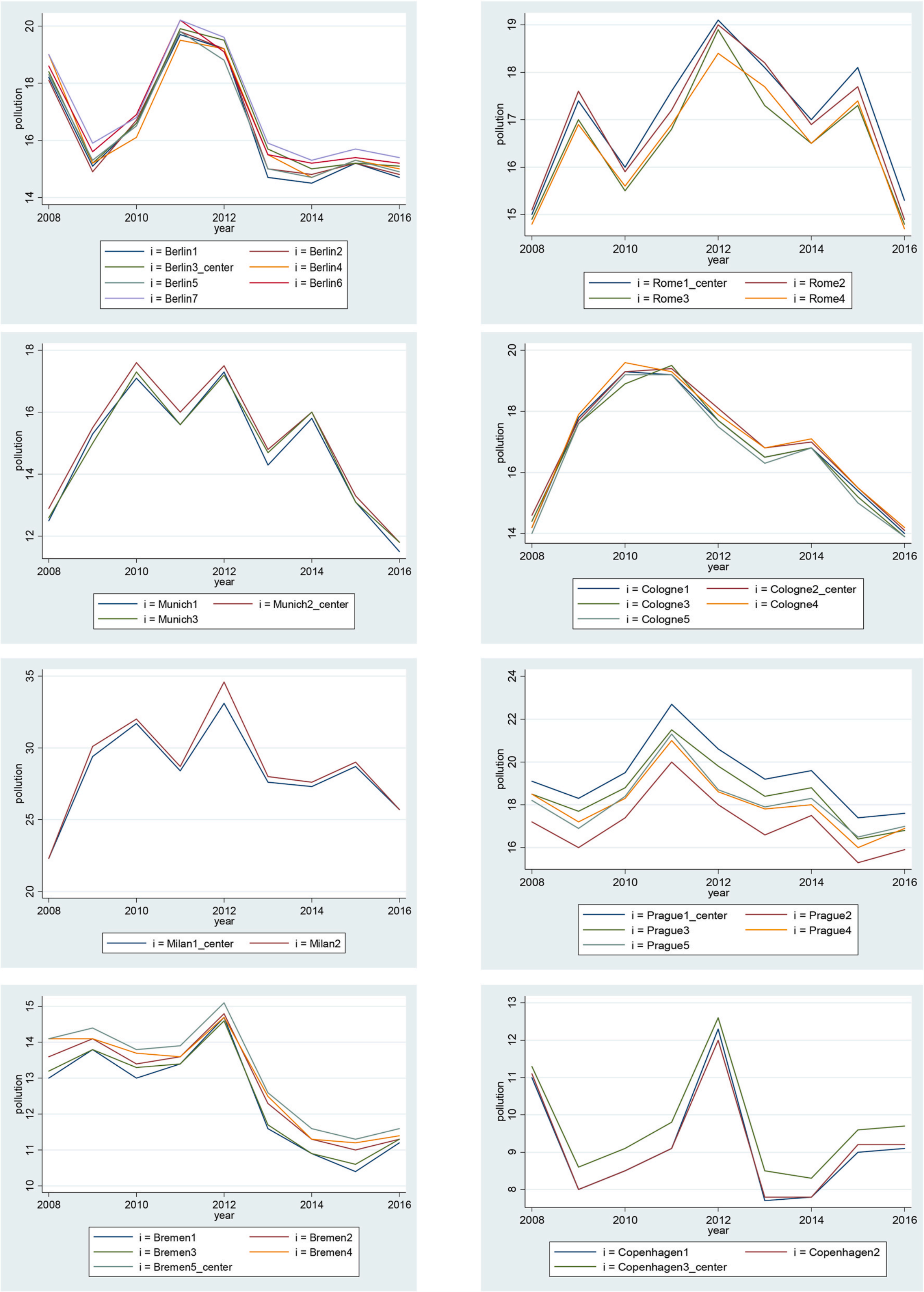

Fig. A1. Evolution of pollution in LEZ cities with several measurement points.

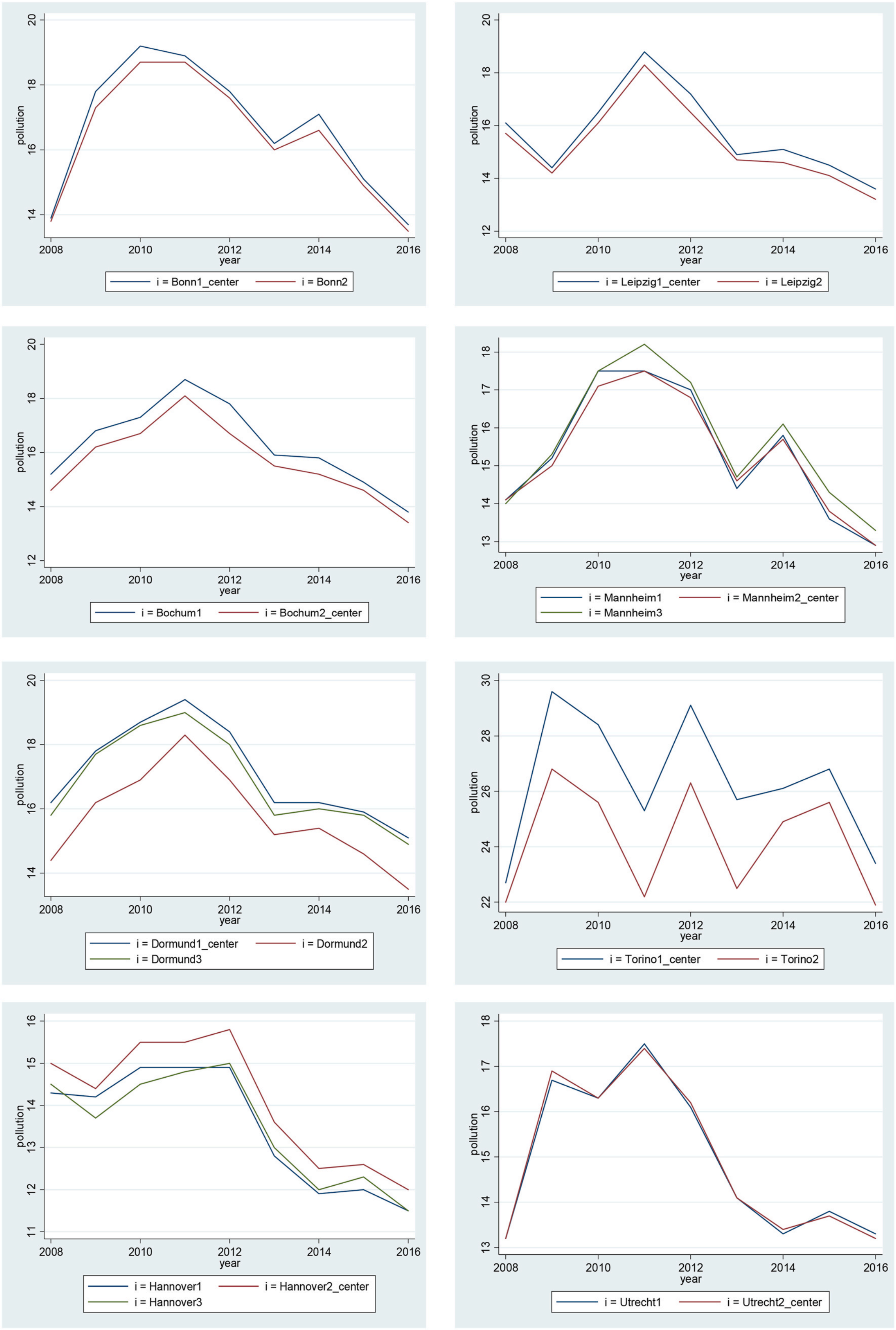

Fig. A1. (*continued*).

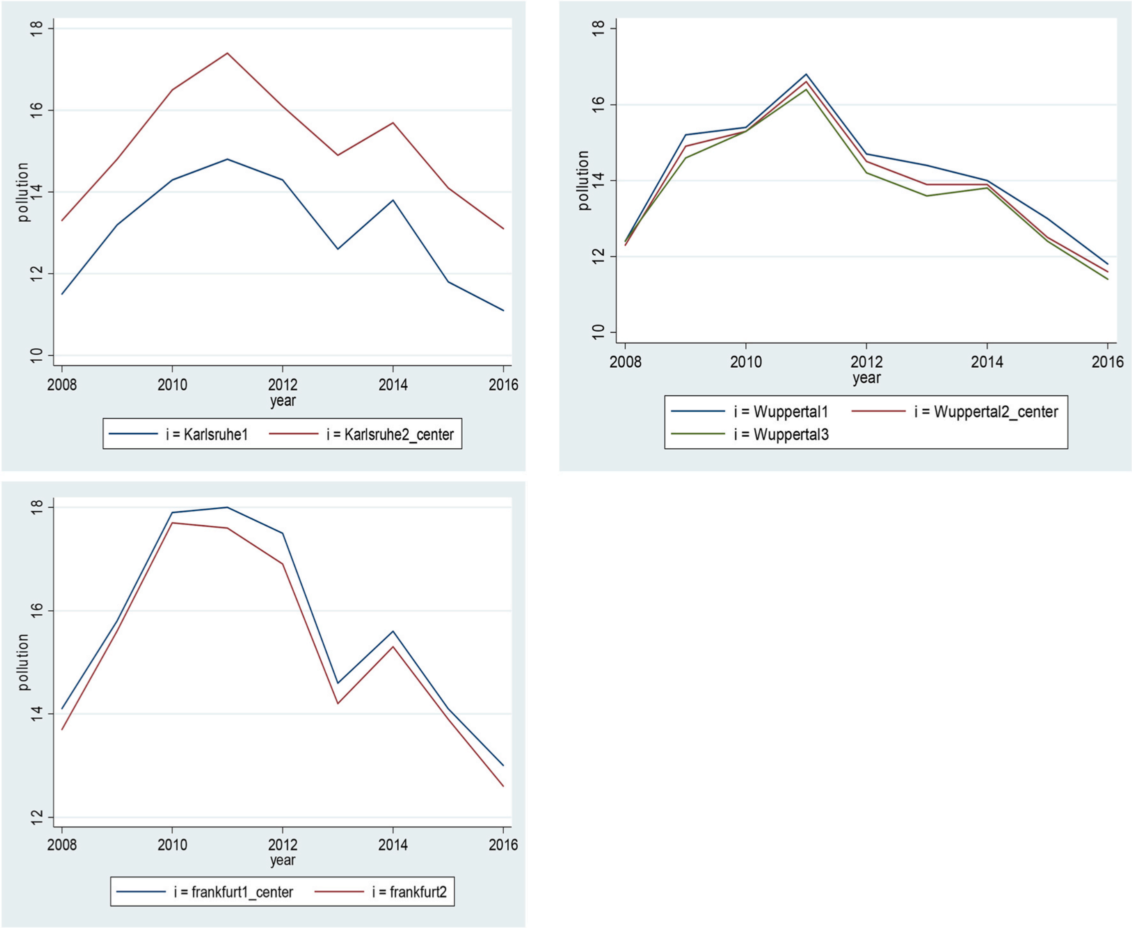

Fig. A1. (*continued*).

CRediT authorship contribution statement

Valeria Bernardo: Conceptualization, Formal analysis, Writing – review & editing. **Xavier Fageda:** Conceptualization, Formal analysis, Writing – review & editing. **Ricardo Flores-Fillol:** Conceptualization, Formal analysis, Writing – review & editing.

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