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How can urban congestion be mitigated? Low emission zones vs. congestion tolls

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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 congestion and pollution. The goal of this paper is to examine, using a panel of large European urban areas over the period 2008-2016, the effectiveness of urban tolls and low emission zones in mitigating urban congestion. We conclude that urban tolls are successful in mitigating congestion. Instead, low emission zones are not effective. This is a very relevant result, given that such policy is being implemented extensively in Europe.

Keywords: congestion; pollution; congestion tolls; low emission zones.

JEL Classification Numbers: D62; H23; L92; R41.

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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 congestion and pollution. 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. 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, and Parry *et al.*, 2007). 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).

Despite the scale of the problem, the competent authorities (basically, the municipalities) do not consider it as a priority. Urban congestion and the pollution it generates are often deemed as an endemic evil inherent to large cities.

Investments in capacity are extremely expensive, involve long gestation periods, and are not effective in urban areas with dense road networks.[1] Therefore, two main types of measures can be applied depending on whether they are quantity-based or price-based. The most popular quantity-based measure in Europe are the low emission zones (LEZ), which are widespread in the continent: they have been implemented in 41 cities from 9 countries.[2] LEZ 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 the pollution levels. Price-based measures consist in charging urban congestion tolls, typically to enter/exit to/from the city center during peak hours. Urban tolls increase divers' 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).[3]

The goal of this paper is to examine the effectiveness of LEZ and congestion tolls in mitigating urban congestion. As far as we know, this is the first study that examines the impact of LEZ on congestion. There are, however, some studies on the effect of LEZ on pollution applied to German cities (Malina and Scheffler, 2015; Morfeld *et al.*, 2014; and Wolff, 2014). In any case, we should expect a positive effect in terms of congestion mitigation (at least in the short-run) as some drivers are banned and may not be able to purchase a *clean* car complying with the LEZ requirements.

The literature on urban congestion pricing is composed by a series of papers that study the effect of urban tolls on individual cities by comparing traffic or congestion levels before and after their implementation. All these studies find congestion pricing to be effective in reducing congestion from the first year of implementation. The analyses for London and Stockholm show that urban tolls reduce congestion by 20-30% (Eliasson, 2008; Santos and Fraser, 2005; and 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; and Percoco, 2013).

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[1] 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.

[2] 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).

[3] 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).

In contrast to the existing literature, we adopt a broader perspective with the ultimate purpose of producing a general assessment on the effectiveness of LEZ and congestion tolls. The effect of other policies, like rail investments or bike-sharing systems, are also analyzed. We use a panel of large European urban areas over the period 2008-2016, so that we can exploit the existing variability among a high number of cities.

In assessing the impact of public policies on congestion, a caveat should be made: there is a potential endogeneity problem as it could be argued that urban tolls and LEZ are mostly applied in severely congested cities. On this matter, two relevant considerations need to be taken into account. First, we propose a fixed effects regression that focuses on cities having applied urban tolls after 2008. In our sample, these cities are Gothenburg and Palermo, which are not particularly congested. Second, the main goal of LEZ is not to mitigate congestion but pollution. Our data does not show a positive relationship between the implementation of LEZ and the congestion level of the urban area. In any case, we apply a matching procedure to control for pre-existing differences (that includes congestion levels) between urban areas applying this policy during the considered period and other areas where LEZ have not been applied.

Our main results are as follows. First, we find that urban tolls are effective in mitigating congestion. The magnitude of the estimated effects is similar to those obtained in previous studies using different methodologies to analyze the effect of tolls on individual cities. The fact that partial studies with very different approaches applied to diverse geographical contexts yield similar results, provides evidence on the robustness of our results. Second, we do not find evidence of LEZ being effective in dealing with urban congestion. This is a very relevant result, given that such policy is being implemented extensively in Europe.

We also conclude that investments in rail transportation help in reducing congestion only when the change in the network is substantial. However, rail infrastructures in many European cities are mature and these investments are very expensive. In addition, such investment decisions may not be under the jurisdiction of local governments. Consequently, rail investments do not seem a valid general solution to address the congestion problems in European cities. Instead, bike-share systems are a cost-effective policy to deal with congestion as they can reduce congestion and the required investment to launch (or improve) them is generally modest.

The material that follows provides some figures on loss of time and pollution related to urban congestion.

Urban congestion and loss of time. Using data from TomTom corresponding to 2016 for cities around the world with a population exceeding 800,000 inhabitants (390 cities in 48 countries on 5 continents),[4] Figure 1 and Table 1 offer a global perspective of the most congested cities on the planet.

– Insert here Figure 1 –

– Insert here Table 1 –

The range of colors in Figure 1 (red, orange, yellow and green) visually reflect the different intensity of the problem in each of the cities under analysis. Congestion is measured in Table 1 as the additional time a vehicle needs to enter/exit to/from a city center as compared to a free flow situation. The congestion value provided in the table is an annual average (the morning and evening rush-hour values appear in the last two columns). In addition, information is also provided on the annual variation with respect to 2015.[5]

Thus, for example, traffic jams in Mexico City make a vehicle take 66% more time on average as compared to an uncongested situation. The economic cost related to this loss of time is huge: the

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

[5] Speed measurements are used to compute travel times on individual road segments and entire networks. Then a ponderation is applied taking into account the number of measurements, where busier and primary roads are given a greater weight.

Confederación Patronal de la República Mexicana estimated that traffic jams in Mexico City in 2016 entailed a loss of 35 million hours per day, which was quantified as an economic damage of $300 million daily.[6] Thus, a driver in Mexico City loses an average of 59 minutes a day in traffic jams, which represents a total of 227 additional travel hours per year.[7]

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.[8]

Although Figure 1 and Table 1 locate the most serious problems in Eastern Asia, congestion is also massively present in European cities. Figure 2 and Table 2 show that congestion is widespread in Europe and that the problem is worsening over time.

– Insert here Figure 2 –

– Insert here Table 2 –

Urban congestion and pollution. 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.[9] The WHO warns that 92% of the population lives in places with a harmful air quality (2014 data) and that air pollution around the world causes 3 million premature deaths each 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.[10] 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).[11] Since our study mainly focuses on urban congestion, Tables 3 and 4 provide information on air pollution in the cities with serious congestion problems listed in Tables 1 and 2.

– Insert here Table 3 –

– Insert here Table 4 –

Table 3 shows the level of pollution registered in the most congested cities in the world. We can see that, although there is no systematic correlation between road congestion and pollution (for instance, Mexico City is more congested but les polluted than Beijing), all severely congested cities

[6] https://es.panampost.com/elena-toledo/2017/02/24/trafico-perdidas-ciudad-de-mexico and http://wipy.tv/60-mil-mdp-perdidas-genera-trafico-la-cdmx.

[7] http://www.animalpolitico.com/2017/02/cdmx-trafico-tomtom.

[8] Information from The Economist (2014).

[9] 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.

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

[11] 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).

register serious pollution records (both PM10 and PM2.5) far superior to the WHO Guideline Values for which there are contrasted negative effects on human health.[12] At European level (see Table 4), the most congested cities also have high pollution rates that, in most cases, exceed the WHO Guide Values. Looking at PM2.5, we find the highest values in Eastern Europe (Warsaw, Bucharest, Sofia, Moscow, and Prague), followed by Central Europe (Prague, Vienna, Paris, and Brussels), although other cities (Rome, Berlin, Amsterdam, London or Athens) also present high values. Therefore, there is not a clear negative correlation between per-capita income and pollution.

Our econometric exercise cannot undertake a sophisticated estimation on the effects of urban tolls and LEZ in mitigating pollution because data for pollution (measured at PM2.5) are only available for 2016. However, with these data, we can delve into the relationship between congestion and pollution. The median spline estimation in Figure 3 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.

– Insert here Figure 3 –

Although the plot in Figure 3 displays an unclear pattern for moderate levels of congestion (up to 35% of additional travel time compared to a free flow situation), we observe that pollution increases exponentially with congestion in an unambiguous way from this threshold onwards. We can therefore conclude that, at least for severely congested cities, reducing pollution unavoidably requires to mitigate congestion.

There is a clear determination on the part of the EU to reduce the registered levels of pollution in cities, especially since the transposition of the directives 1999/30/EC and 2008/50/EC.[13] This determination has been accompanied by the establishment of the 'Euro' regulatory standards for vehicles sold in the member states.[14] Quite clearly, LEZ have been the main policy chosen by the European municipalities to accomplish the objectives in the aforementioned directives. However, the effectiveness of LEZ on pollution may be conditioned by its effects on congestion, particularly in those cities where the latter is particularly high.

The rest of the paper is organized as follows. Section 2 shows how urban congestion is modeled from a microeconomic viewpoint and the theoretical effects of congestion tolls and LEZ. In Section 3 we present the empirical equation along with the data that are used to build our main variables. Section 4 delivers our main results. Finally, Section 5 provides some final considerations.

2. A simple model to explain the effect of low emission zones and congestion tolls

In this section, we first provide a welfare analysis explaining the excess traffic and the inefficiency associated with urban congestion. Then, using this framework, we explain the effect of congestion tolls and LEZ. Finally, we incorporate pollution into the analysis and we provide an overall assessment of both measures. This assessment proposes four different scenarios depending on the relative effectiveness of congestion tolls and LEZ that can guide the empirical analysis that is conducted afterwards.

2.1 The excess traffic generated by urban congestion

Urban congestion is a negative externality that appears when traffic volume exceeds a certain threshold. The textbook model (see, e.g., Brueckner, 2011; Lindsey and Verhoef, 2001; or Cantillo and Ortúzar, 2014) assumes that the time that a vehicle needs to enter/exit to/from the city center (t) is a function of the traffic volume (q), so that $t = f(q)$. From this function, we can build another one that represents the total time needed by all vehicles to enter/exit to/from the city center $qt = qf(q)$.

[12] The extreme indices registered in Chinese cities (Chongqing, Chengdu, and Beijing), are explained by the pollution produced by automobiles, but also by the combustion of coal in homes, factories of all types, and thermal power plants located in the vicinity of cities. Instead, cars are unambiguously the major contributor to air pollution in European cities.
[13] 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.
[14] https://en.wikipedia.org/wiki/European_emission_standards.

Finally, we can analyze the increase in total time that represents the introduction of a new vehicle $\partial qt/\partial q = t + q\partial t/\partial q$. The second term of the expression identifies the negative externality that a new vehicle represents for the rest of drivers.[15]

At this point, we can define the congestion threshold $\tilde{q}$ so that, for $q < \tilde{q}$, the introduction of a new vehicle does not generate any externality and, therefore, $\partial t/\partial q = 0$. Instead, for $q > \tilde{q}$, the introduction of a new vehicle represents a negative externality for the rest of users and $\partial t/\partial q > 0$. Figure 4 summarizes this situation.[16] Graphically, the externality $q\partial t/\partial q$ is the vertical distance between the functions t and $\partial qt/\partial q$.

– Insert here Figure 4 –

From a wider point of view, we can reinterpret the time that a vehicle needs to enter/exit to/from the city center (t) as the generalized travel cost. In this case, the expressions t and $\partial qt/\partial q$ can be understood as the average private cost and the marginal social cost associated to the trip and can be graphically represented as the private supply (S_P) and the social supply (S_S), respectively. Finally, if we incorporate in the analysis a downward-sloping demand for travel (D), we obtain the equilibrium represented in Figure 5 as the intersection between demand and supply, which results in a volume of traffic q^* and an individual cost t_p^*. Instead, the presence of congestion, increases the social cost to t_s^*. We can also represent the social optimum (q^{SO}, t^{SO}) from equaling the demand to the social supply. The social optimum is efficient because drivers internalize the congestion they impose on other road users. Therefore, the difference $q^* - q^{SO}$ indicates the excess traffic observed in equilibrium as compared to the social optimum.

The figure also shows the social welfare associated with car usage as the difference between the drivers' valuations (given by their demand D) and its social cost (given by S_S). This difference is positive and constitutes a welfare gain (striped area) for $q < q^{SO}$, and negative implying a welfare loss for $q > q^{SO}$ (shaded area).

– Insert here Figure 5 –

2.2 Measures: congestion tolls vs. LEZ

In this situation, two types of measures can be considered depending on whether they are based on either reducing the quantity or increasing the travel cost.

Price measures: congestion tolls. A congestion toll consists in increasing the average private cost (t) up to the marginal social cost ($\partial qt/\partial q$). Thus, the optimal amount of the toll to recover the efficiency and eliminate the excess traffic would be precisely the externality $t_s^* - t_p^* = q^*\partial t/\partial q$. In such a way, the externality would be internalized and some additional revenue would be raised.

Quantity measures: LEZ. The implementation of LEZ aims at reducing the demand for travel. In case the contraction of demand would exactly eliminate the excess traffic, we would get the situation represented in Figure 6 where $q^* = q^{SO}$.

– Insert here Figure 6 –

Therefore, both congestion tolls and LEZ can be equally effective in eliminating the excess traffic if they are correctly designed. However, quantity measures generate welfare losses (new shaded area in Figure 6) because they do not take into account drivers' valuations and are applied indiscriminately.

2.3 Extension of the model to incorporate pollution

[15] In the case of airport congestion, the analysis is different to the one presented here. The reason is that airlines typically have market power (contrary to road users that are atomistic) and, therefore, internalize part of the congestion they generate (see Brueckner, 2002; and Mayer and Sinai, 2003).

[16] The empirical studies on congestion conclude that the time a vehicle needs to circulate on a congested road increases exponentially with respect to the traffic volume (OECD, 2007). This is the reason by which the function t is increasing and convex with respect to q, i.e., $\partial t/\partial q > 0$ and $\partial^2 t/\partial q^2 > 0$, as shown in Figure 4.

Let us consider now that there are two types of cars, new and old, so that the traffic volume is $q = \lambda q_{old} + (1-\lambda)q_{new}$, where λ and $1-\lambda$ are the shares of each car type. We suppose that new cars are clean and produce 0-emissions (i.e., electric cars), so that car pollution is given by $P = g(q_{old})$, with $g'(q_{old}) > 0$.[17] Therefore, although both congestion tolls and LEZ can eliminate the excess traffic $q^* - q^{SO}$ generated by congestion, their effect on pollution is different with LEZ being in general more effective. The reason is that congestion tolls do not discriminate between new and old cars, whereas LEZ only restrict the access to old cars. Of course, the different effectiveness between both measures in mitigating pollution depends on the extent of λ. Logically, the proportion of old cars λ tends to decrease over time as the fleet is renewed. Additionally, as LEZ are announced some time before they are made effective, a certain accommodative behavior of local drivers can accelerate this car renewal process. In any case, our variable captures the short-term effects of the policy, taking into account that the long-term effects may be less important in terms of congestion mitigation as more drivers can renew their cars over time.

2.4 Overall assessment of congestion tolls and LEZ

All in all, when assessing the performance of congestion tolls and LEZ, we need to take into account their effect on both externalities: excess traffic and pollution. Looking at the excess traffic externality, congestion tolls are always better than LEZ because they are more efficient (because they take into account drivers' valuations) and at least equally effective, with the effectiveness of LEZ depending on the level of λ. Looking at the pollution externality, the performance of LEZ is better than the one of congestion tolls, with the difference between the two depending again on the level of λ. At this point, we can consider four scenarios.

- Scenario 1: $\lambda = 0$. There are no polluting cars and, therefore, LEZ produce no effects and are useless. Differently, congestion tolls can eliminate the excess traffic.
- Scenario 2: $\lambda \in (0,1)$ low so that LEZ cannot eliminate completely the excess traffic by just reducing the amount of old cars. In this case, LEZ are less effective than congestion tolls in reducing the excess traffic but they are superior in reducing pollution (as they eradicate it by blocking every old car).
- Scenario 3: $\lambda \in (0,1)$ high so that LEZ can eliminate the excess traffic by just reducing the amount of old cars. In this case, LEZ and congestion tolls are equally effective in reducing the excess traffic and LEZ are superior in reducing pollution.
- Scenario 4: $\lambda = 1$. All cars are polluting and both LEZ and congestion tolls are equally effective in reducing both excess traffic and pollution.

Although à priori Scenario 3 seems to be plausible, our empirical application finds clear evidence of Scenario 2 for the considered sample.

3. **Empirical equation and data**

We estimate the following equation for the urban area *u* at year *t*:

$$\log(Congestion)_{ut} = \alpha + \beta_1 D_{ut}^{Tolls} + \beta_2 D_{ut}^{LEZ\_general} + \beta_3 D_{ut}^{LEZ\_trucks} + \beta_4 D_{ut}^{BSS} + \beta_5 Rail\_ntwk_{ut} + \beta_5 \log(Pop)_{ut} + \beta_6 \log(Density\_region)_{ut} + \beta_7 \log(Density\_main\_city)_{ut} + \beta_8 \log(GDPpc)_{ut} + + \lambda' Urban\_area + \gamma' Year + \varepsilon,$$

where all continuous variables without zero values are transformed using logarithms, so that the influence of outliers is reduced and parameter estimates can be interpreted as elasticities.

The dependent variable ($\log(Congestion)$) measures the additional time a vehicle needs to enter/exit to/from a city center as compared to a free flow situation (data from TomTom).[18] The main

[17] A more sophisticated analysis can be done by assuming a distribution of cars in terms of their age and modeling emissions as an increasing function of the fleet's age. However, our theoretical intuitions would remain qualitatively unchanged.

[18] The same measure of congestion has been used in the elaboration of Figures 1-2 and Tables 1-2.

explanatory variables are four dummies accounting for the main policies currently applied in Europe to mitigate congestion: congestion tolls, general LEZ applicable to all vehicles, LEZ for trucks, and bike-sharing systems (D^{Tolls}, $D^{LEZ\_general}$, D^{LEZ_trucks}, and D^{BSS}). Controls include urban area attributes ($\log(Pop)$, $\log(Density\_region)$, $\log(Density\_main\_city)$, and $\log(GDPpc)$) and the length of the rail network ($Rail\_ntwk$), which is replaced by the presence of new rail lines ($Rail\_new$) in an additional regression. Furthermore, some specifications include interactions between the LEZ variable and income ($D^{LEZ_{general}} x\log(GDPpc)$) or between the LEZ variable and an additional variable that measures the proportion of new cars ($D^{LEZ\_general} xProp\_new\_cars$). In this latter regression, we also add the uninteracted variable for the proportion of new cars ($Prop\_new\_cars$).

Our sample is based on urban areas within the EU. The definition of the urban area and the population data have been obtained from United Nations (World Urbanization Prospects). We limit the sample to areas with a population exceeding 300,000 inhabitants to have comparable cities as congestion concerns in small cities should be modest. The considered period is 2008-2016. This time span is determined by the availability of congestion data, which is the dependent variable in our analysis. Overall, our sample has 1162 observations with information for 130 cities from 19 different countries.

We take into account three different attributes of urban areas as potential drivers of congestion: population, density, and income. First, we include the population at the urban level ($\log(Pop)$ variable). Previous studies typically consider population as a relevant factor of congestion. A superlinear relationship between urban size and congestion is generally expected, so that the coefficient of the population variable is expected to exceed 1.[19]

Second, we include two variables to capture the density of the main city and the region that surrounds it (data from Eurostat). More precisely, we incorporate *i)* the population-density at the NUTS-3 level (region) where the urban area is located ($\log(Density\_region)$ variable), and *ii)* the proportion of the core-city population over total population of the urban area ($\log(Density\_main\_city)$ variable). The relationship between urban density and congestion is unclear as denser cities are characterized by a lower number of vehicle/kilometers traveled but traffic is concentrated in fewer points.[20]

Third, we also consider the income of the urban area by incorporating the regional GDP per capita in purchasing power standards ($\log(GDPpc)$ variable) at the NUTS-2 level (using data from Eurostat). Unfortunately, more disaggregated data are not available for the considered period. The relationship between income and congestion is again unclear. Although a positive relationship makes sense as the number of car trips in richer urban areas is typically higher, it is also true that richer areas have better infrastructures (including roads and all types of public transportation means) that could mitigate congestion.

Finally, 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 kilometers of rail lines ($Rail\_ntwk$ variable), which includes metro, light trains, trams, and local trains (using data from the World Metro Database).[21] Furthermore, we also consider a variable that captures the presence of new rail lines ($Rail\_new$ variable). A recent review by Beaudoin *et al.* (2015) suggests that better public transportation options can help in reducing congestion, with the magnitude of such effects being specific of each particular location.

After controlling for all these factors, we shift our attention to the four dummy variables capturing the most relevant policies currently applied in Europe that can have an effect in mitigating congestion: congestion tolls, general LEZ applicable to all vehicles, LEZ for trucks, and bike-sharing systems (variables D^{Tolls}, $D^{LEZ\_general}$, D^{LEZ_trucks}, and D^{BSS}). We use the information provided by CLARS (Charging, Low Emission Zones, other Access Regulation Schemes), a website promoted

[19] See Chang *et al.* (2017).
[20] See Ewing *et al.* (2014 and 2018), Sarzynski *et al.* (2006), and Su (2010).
[21] http://mic-ro.com/metro/table.html.

by the European Commission and built by Sadler Consultants Ltd.[22] These data are complemented with information from the 'European city ranking 2015: best practices for clean air in urban transport',[23] the EcoRegion project,[24] and city regulations searched online.

Congestion tolls are applied in a restricted area of the core city. Previous studies have examined their impact on individual cities by comparing either traffic or congestion levels before and after their implementation. All these studies find congestion pricing to be effective in reducing congestion from the first year of implementation. The analyses for London and Stockholm show that urban tolls reduce congestion by 20-30%,[25] while the impact is about 10-15% in Milan and Gothenburg.[26]

LEZ ban polluting vehicles (i.e., those not complying with emission standards) from city centers. We distinguish between general LEZ (applicable to all vehicles) and LEZ just for trucks.[27] The primary goal of this policy is not to mitigate congestion but to reduce the pollution levels.[28] Previous studies for German cities suggest that this policy can be effective in improving the air quality.[29] As far as we know, no previous study has examined the impact of LEZ on congestion. At least in the short-term, we could expect a positive effect in terms of congestion as some drivers are banned (and may not be able to purchase a *clean* car complying with the LEZ requirements). In the same way, we also expect a more modest effect of this policy in richer cities with newer cars (that are more likely to meet the emission standards) and more possibilities to replace old cars by new ones. This is the reason why we add an interaction term between the income variable and the dummy for LEZ. Furthermore, we add a new variable in a complementary regression indicating the percentage of passenger-cars with 5 years or less over total passenger-cars ($Prop\_new\_cars$) and then we interact it with the LEZ variable ($D^{LEZ\_general}xProp\_new\_cars$). Unfortunately, Eurostat only provides information for this variable at the country level.

Although bike-sharing systems (BSS) may have different purposes like reducing pollution or promoting a healthy life, they also aim at reducing congestion. BSS constitute an alternative to cars for short trips and, additionally, they also extend the public transportation network within an urban area. However, whenever BSS come together with more bike lanes, the space for cars is typically reduced. This is why the literature studying the effect of BSS on congestion shows mixed results. Using fuel consumption as a proxy for congestion for a panel data of 96 US cities during the period 2005-2014, Wang and Zhou (2017) find that the positive effects of BSS on congestion concentrate on larger cities and that the effect in richer cities can be negative. In another study centered in Washington DC, Hamilton and Wichman (2018) conclude that BSS reduce congestion up to 4% in neighborhoods having available stations, with this effect being stronger in the most congested neighborhoods.

Table 5 shows the cities in our sample that have implemented any of the aforementioned policies. BSS seem to be popular, as they are present in 92 cities from 17 countries. LEZ are also widespread in Europe: they have been implemented in 41 cities from 9 countries. Differently, very few cities have put into practice urban congestion tolls. We can only identify the change from a situation without tolls to another one with tolls in Gothenburg and Palermo, i.e., the two cities that have implemented a toll system after 2008.

– Insert here Table 5 –

[22] http://urbanaccessregulations.eu.

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

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

[25] See Eliasson (2008), Santos and Fraser (2005), and Börjesson *et al.* (2012 and 2014).

[26] See Andersson and Nässén (2016), Gibson and Carnovale (2015), Rotaris *et al.* (2010), and Percoco (2013).

[27] Although there may be different requirement levels in the application of LEZ, we do not find relevant differences in our results when they are taken into account. Therefore, we simply identify whether LEZ have been implemented or not.

[28] Several studies show that congestion has a strong impact on pollution in urban areas (see Barth and Boriboonsomsin, 2008; Beaudoin *et al.*, 2015, and Parry *et al.*, 2007). The median spline estimation in Figure 3 shows the relationship between pollution and congestion in our sample of European cities.

[29] See Malina and Scheffler (2015), Morfeld *et al.* (2014), and Wolff (2014).

4. Results

Table 6 shows some descriptive statistics. As it can be observed, the *between variation* is always higher than the *within variation*, meaning that differences between urban areas are higher than differences within urban areas over time. Congestion is high on average: 25% of extra-time as compared to an uncongested situation. Its variation over time is low, a fact that suggests that the problem of congestion is persistent.

– Insert here Table 6 –

Figures 7 and 8 show histograms of the congestion variable for the initial and final year of the considered period (annual averages). In both periods, a high proportion of cities have congestion levels within the range 20-30%. As shown in Table 2, morning and evening rush-hour values are substantially higher.

– Insert here Figures 7 and 8 –

Table 7 shows the Variance Inflation Factors (VIF) of the explanatory variables used in the empirical analysis. Multicollinearity can exaggerate estimates of the variance parameter and distort its statistical significance, even resulting in parameter estimates of implausible magnitude in the most extreme cases. VIF are widely used to examine the degree of multicollinearity between explanatory variables. Several rules of thumb for VIF have been used as a sign of severe multicollinearity. The one typically considered in Econometrics textbooks is 10, although practitioners may use lower threshold values, with 5 being a commonly used value. The values reported in Table 7 are clearly below 5 for all the variables.

– Insert here Table 7 –

Estimates may present heteroscedasticity problems and temporal autocorrelation in the error term. On the one hand, the Wooldridge test for autocorrelation in panel data reveals that a problem of serial autocorrelation may exist. On the other hand, the Breusch-Pagan/Cook-Weisberg test shows no heteroscedasticity problems.

We estimate a *pooled model* without urban area fixed effects and a *fixed effects model* (using several specifications) that incorporates urban area dummies. Note that standard errors are clustered at the urban level in all regressions to account for the correlation of observations within each urban area.

The pooled model identifies the aggregate effect over a period and, therefore, it is not useful in examining changes associated with the implementation of a certain policy. However, it allows us to quantify the mean congestion outcomes in urban areas that have implemented the considered policies. In addition, it exploits the between and within variation of the data.

The fixed effects model identifies changes from one period to another and, therefore, is the most appropriate method to evaluate the effect of urban policies on congestion. It is based on the within transformation of the variables as deviations from their average. Thus, the model allows to compare changes in congestion outcomes between urban areas that have implemented policies and others that have not. Furthermore, it controls for omitted, time-invariant variables correlated with the variables of interest. Since the effect of time-invariant variables cannot be captured as they are absorbed by the fixed effects, we can only measure the impact of the policies implemented after 2008. Of course, a limitation of our analysis has to do with the low within variation that characterizes our sample.

Results of the pooled model.

In the results of the pooled model reported in Table 8, all the coefficients of urban area attributes are statistically significant. As expected, bigger cities are more congested although the magnitude of the coefficient does not confirm a superlinear relationship. The results also show that denser cities in denser regions are more congested, suggesting that the effect of the concentration of traffic in fewer points more than compensates the lower number of vehicle/kilometers traveled. Somewhat surprisingly, richer urban areas are less congested on average, suggesting that having better infrastructures more than compensates the higher number of car trips that is expected in richer urban areas. Quite consistently with the positive effect of income in reducing congestion, we also observe that cities with better rail networks are less congested (see coefficient of $Rail\_ntwk$).

– Insert here Table 8 –

Regarding the policy variables, we find that urban tolls are applied in more congested cities. This finding could be perceived as a sign of endogeneity when analyzing the impact of changes in the fixed effects regression. However, the fixed effects regression can only identify the effect of congestion pricing in cities that have implemented it after 2008. In our sample, these cities are Gothenburg and Palermo, which that are not particularly congested.

Other policies like the LEZ and BSS do not seem to be applied in more congested cities. It should be recalled that the main goal of LEZ is to fight against pollution (and not against congestion), while BSS may also have other purposes beyond congestion (like reducing pollution or promoting a healthy life). Furthermore, both policies are applied in a high number of cities. The implementation of LEZ for trucks produces a negative statistical effect (at 10%), meaning that this policy is applied in less congested cities.

Results of the fixed effects model.

Looking at urban area attributes, we observe that the coefficient of the two density variables ($\log(Density\_region)$ and $\log(Density\_main\_city)$) loses its statistical impact. The low within variation of these variables explains this result, as the urban area fixed effects may be capturing their effects. By contrast, the fixed effects model provides the expected results for the coefficients of the $\log(Pop)$ and the $\log(GDPpc)$ variables. Indeed, we find the expected superlinear relationship between population and congestion, meaning that more populated urban areas suffer a more than proportional increase in congestion. Furthermore, richer cities are more congested. The change in the sign of the income variable can be explained by urban area fixed effects capturing the effect associated with better infrastructures (that have a low within variation).

– Insert here Table 9 –

Our results suggest that better rail networks reduce congestion, although this effect is not statistically significant (see coefficient of $Rail\_ntwk$). The low within variation of this variable can explain this absence of significance and, therefore, we cannot conclude that investments in public transportation are ineffective in reducing congestion.

Specification II incorporates a new variable to account for the presence of new rail lines ($Rail\_new$ variable), which characterizes urban areas that have experienced a substantial improvement in their rail networks. The coefficient of this variable is statistically significant at the 10% level, suggesting that rail public transportation helps in reducing congestion mostly when it is substantially improved. However, this is an extremely expensive way to deal with congestion and many of the urban areas in our sample have already dense public transportation networks. Consequently, in the majority of the considered urban areas, only marginal improvements will be feasible in the coming years.

Regarding the policy variables, we find clear evidence on the effectiveness of congestion pricing in reducing congestion (see coefficient of D^{Tolls}). The magnitude of the impact is about 10%. Interestingly, the same result is found in a study based on Gothenburg (Andersson and Nässén, 2016). Thus, we find an additional evidence on the effectiveness of this policy even if it is applied only in few cities.

Furthermore, we also find that BSS may contribute to reduce congestion. The effect is modest but still significant at the 10% level. The magnitude of the impact is about 3%, which is similar to the result obtained in a study based on Washington DC (Hamilton and Wichman, 2018). At this point, it is interesting to emphasize that the required investments to launch (or improve) BSS are generally modest, especially when we compare them with the ultra-expensive investments that are required to improve rail networks. Therefore, investments in BSS seem to be a cost-effective policy to deal with congestion.

On the effect of LEZ on congestion, our results show that they do not contribute to the mitigation of congestion (see coefficient of $D^{LEZ\_general}$ and D^{LEZ_trucks} in specifications I and II). This is a very relevant result, given that this policy is being implemented extensively in Europe. Although LEZ's main purpose is to reduce pollution, our results call into question the effectiveness of this policy given the strong relationship between congestion and pollution (Barth and Boriboonsomsin, 2008; Beaudoin *et al.*, 2015, and Parry *et al.*, 2007). As we have shown in our previous median spline estimation, such relationship can be expected to be particularly strong for highly congested cities (see Figure 3).

Having said this, we now look at the differential effects of LEZ in richer cities (specification III) and cities with a higher proportion of new vehicles (specification IV), as we expect weaker effects of this policy in such cities.

In specification III, we add an interaction term between the LEZ and the income variables ($D^{LEZ_{general}}x\log(GDPpc)$). In the presence of this interaction term, the coefficient of the LEZ variable becomes negative whereas the coefficient of the interaction term shows a positive sign. These results suggest a stronger impact of LEZ in poorer cities, although the effects are not statistically significant. Thus, although richer citizens should have newer cars and more possibilities to replace old cars by new ones (that are more likely to meet the emission standards), our additional estimation does not find conclusive evidence of LEZ being more effective in poorer cities. This result is probably explained by the aggregated nature of our data, which can *hide* differences between citizens within each city.

Specification IV incorporates a variable measuring the proportion of new vehicles ($Prop\_new\_cars$) along with an interaction term between it and the LEZ variable ($D^{LEZ\_general}xProp\_new\_cars$). In this specification, both the coefficient of the LEZ variable and the one of the interaction term are statistically significant. The first one is negative whereas the second one shows a positive sign. Therefore, we conclude that LEZ could be effective in reducing congestion in cities where the proportion of new cars is lower.

A potential endogeneity problem could arise if urban tolls and LEZ are mostly applied in severely congested cities. On this matter, two relevant considerations need to be taken into account. First, our fixed effects regression focuses on cities having applied urban tolls after 2008. In our sample, these cities are Gothenburg and Palermo, which are not particularly congested. Second, the main goal of LEZ is not to mitigate congestion but pollution. Our data does not show a positive relationship between the implementation of LEZ and the congestion level of the urban area. In any case, as a robustness check, a matching procedure is applied in specification V to control for pre-existing differences (that includes congestion levels) between urban areas applying this policy during the considered period and other areas where LEZ have not been applied.

The matching procedure consists in re-estimating the equation for the determinants of urban congestion with the observations that have common support. The purpose of this estimation is to correct for possible concerns on the bias of the estimated coefficient of the LEZ variable due to pre-existing differences between urban areas applying this policy during the consider period and other areas where LEZ have not been applied. Matching procedures eliminate this potential bias by pairing observations with similar characteristics from the treated group (urban areas with LEZ) and the control group (urban areas without LEZ).

Following Rosenbaum and Rubin (1983), we first estimate the probability of being treated conditional on the pre-existing characteristics that differ between groups with a certain logistic model, obtaining the propensity score for each observation. In a second step, we match the observations between the treated and the control groups on the basis of the propensity score using the *first nearest neighbour algorithm* (that matches treated and control observations having the closest propensity score). We then drop all the observations without common support and re-estimate our equation of interest based exclusively on the matching sample.

Table A1 in the Appendix shows the results of the estimated probability of being treated (i.e., implementation of the LEZ) conditional on different urban characteristics. To obtain the propensity score for each observation, we use data from the initial year of the considered period for all continuous explanatory variables (including $Prop\_new\_cars$) and the levels of congestion. The remaining policy dummies are not included in order not to reduce further the sample matching, which would jeopardize the feasibility of the regression.

Results in Table A1 provide mixed evidence on the potential effectiveness of LEZ. The fact that LEZ are more likely to be applied in richer and less congested cities suggests a limited effectiveness of this policy. However, the results also show that LEZ are less likely to be applied in cities with a higher proportion of new cars, which suggests a high potential effectiveness of this policy. Any potential endogeneity bias should lead to an over-estimation of the impact of LEZ in reducing congestion, as less congested cities are more prone to apply them.[30]

Coming back to specification V in Table 9, the matching sample contains 31 urban areas from the treated group and 31 urban areas from the control group. The results of this additional regression confirm our previous finding on the ineffectiveness of LEZ in reducing congestion.

All in all, we do not find any conclusive evidence of LEZ being effective in dealing with urban congestion. A caveat that can be made has to do with the fact that our data on LEZ is limited to their implementation date. However, in reality, LEZ are announced some time before they are made effective, allowing for a certain accommodative behavior of citizens. In any case, our variable captures the short-term effects of the policy, taking into account that the long-term effects may be less important in terms of congestion mitigation as more drivers can renew their cars over time. Note also that our analysis focuses on a sample of relatively wealthy cities, so the effect of the LEZ on congestion could be more relevant in cities with lower income levels.

Recalling the theoretical scenarios considered in Section 2, we find strong empirical evidence of Scenario 2 for the considered sample of European cities during the period 2008-2016. More precisely, the ineffectiveness of LEZ in mitigating congestion suggests the existence of a low proportion of polluting cars (λ). In other words, LEZ seem to be applied in European cities with renovated car fleets and, consequently, they cannot have substantial effects in reducing traffic and congestion. Given this result and acknowledging that pollution comes mainly from car emissions, we can also infer a limited effect of LEZ in terms of air quality improvements (a fact that is confirmed in Morfeld *et al.*, 2014).

5. Conclusion and discussion

This paper is the first to examine from a broad perspective the effectiveness of LEZ and urban tolls in mitigating congestion. We conclude that urban tolls (and, to a lower extent, bike-share systems) can be effective in mitigating congestion. Instead, LEZ are ineffective. This is a very relevant result as LEZ have been the main policy chosen by the European municipalities to accomplish the pollution objectives established by the EU regulation.

Despite being the most effective policy in dealing with congestion, urban congestion tolls are just applied by few cities. By contrast, LEZ are massively applied in European cities despite being ineffective in mitigating congestion. This observation suggests that pollution (and not congestion) is the main policy objective for most of European cities.

In any case, urban congestion tolls can be seen as a superior tool as they can mitigate simultaneously pollution and congestion (the relationship between them is incontestable). The ultimate reason behind the underuse of urban congestion tolls has to do with their unpopularity because they 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.

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[30] As the main objective of LEZ is to mitigate pollution, this potential endogeneity problem is also reduced.

However, this lack of social and political support seems to be a short-run effect. In Stockholm, social support for congestion tolls went from 30% before the application to 70% (Eliasson, 2008) one year after its implementation, once the citizens could experience the effectiveness of the toll (traffic fell by 20% shortly after its implementation).[31]

Although a recurrent argument against congestion charges is related to do with their supposedly regressive effects, the main reason for their unpopularity has to do with drivers' self-interest (Hamilton *et al.*, 2014). On the equity effects of congestion pricing, some considerations can be made.[32] First of all, the funds obtained from the toll are typically used to improve public transportation (whose users generally do not own a private vehicle and earn lower incomes than car owners).[33] Second, the mitigation of congestion reduces commuting times and, therefore, fuel consumption (which constitutes a direct benefit for drivers). Third, as compared to LEZ, tolls are unequivocally more redistributive since LEZ do not raise any funds and harm the owners of older cars that cannot replace them by new ones meeting the emission standards.

[31] There are also evidences of increased public support for congestion pricing in other cities such as London, Milan, Gothenburg, and Singapore (Börjesson *et al.*, 2016).

[32] A review of the literature on the equity effects of congestion pricing can be found in Eliasson (2016).

[33] Taking this consideration into account, Eliasson and Mattsson (2006) find that the toll system in Stockholm is actually progressive.

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Tables

Table 1: Ranking of *top ten* most congested cities in the world.

World ranking	City	Congestion	Variation	Morning peak	Evening peak
1	Mexico City	66%	+7%	96%	101%
2	Bangkok	61%	+4%	91%	118%
3	Jakarta	58%	–	63%	95%
4	Chongqing	52%	+14%	90%	94%
5	Bucharest	50%	+7%	90%	98%
6	Istanbul	49%	-1%	63%	91%
7	Chengdu	47%	+6%	74%	79%
8	Rio de Janeiro	47%	0%	63%	81%
9	Tainan	46%	+10%	51%	71%
10	Beijing	46%	+8%	72%	84%

Table 2: Ranking of most congested European capital cities.

European ranking	World ranking	City	Congestion	Variation	Morning peak	Evening peak
1	5	Bucharest	50%	+7%	90%	98%
2	13	Moscow	44%	0%	71%	94%
4	25	London	40%	+2%	64%	68%
6	27	Rome	40%	+2%	74%	68%
7	35	Paris	38%	+2%	68%	66%
8	37	Brussels	38%	+3%	71%	77%
10	41	Athens	37%	+1%	58%	56%
11	42	Warsaw	37%	-1%	65%	72%
17	67	Vienna	31%	+3%	46%	54%
23	81	Oslo	30%	+5%	57%	69%
24	83	Sofia	29%	–	58%	66%
25	84	Berlin	29%	+1%	43%	50%
28	92	Stockholm	28%	-1%	48%	61%
30	94	Prague	28%	+1%	54%	46%
34	112	Madrid	25%	+2%	48%	43%
40	129	Amsterdam	22%	+2%	35%	52%

Table 3: Pollution in the *top ten* most congested cities in the world.

City	PM10 (average annual µg/m^3)	PM2.5 (average annual µg/m^3)
Mexico City	42	20
Bangkok	42	24
Chongqing	106	61
Bucharest	31	23
Istanbul	53	33
Chengdu	150	71
Rio de Janeiro	49	16
Tainan	44	29
Beijing	108	85

Table 4: Pollution in the most congested European capital cities.

City	PM10 (average annual μg/m^3)	PM2.5 (average annual μg/m^3)
Bucharest	31	23
Moscow	33	20
London	22	15
Rome	28	17
Paris	28	18
Brussels	26	18
Athens	40	15
Warsaw	33	26
Vienna	26	18
Oslo	22	11
Sofia	43	22
Berlin	24	16
Stockholm	26	6
Prague	27	19
Madrid	19	10
Amsterdam	23	16

Table 5. Urban transport policies and cities of the sample.

Policy	Cites by country
LEZ for trucks	**Austria:** Vienna (2008). **Italy:** Verona (2011). **Netherlands:** Amsterdam (2008), Eindhoven (2007), The Hague (2008), Utrecht (2007). **Sweden:** Gothenburg (1996), Stockholm (1996). **UK:** London (2008).
LEZ (general)	**Czech Republic:** Prague (2016). **Denmark:** Copenhagen (2008). **Germany:** Berlin (2008), Bonn (2010), Bremen (2010), Cologne (2012), Dortmund (2013), Düsseldorf (2009), Duisburg (2013), Essen (2013), Frankfurt (2010), Hannover (2010), Karlsruhe (2013), Leipzig (2011), Mannheim (2013), Muenster (2010), Munich (2012), Stuttgart (2010), Wuppertal (2011). **Italy:** Bologna (2016), Florence (2008), Genoa (2016), Milan (2008), Modena (2016), Naples (2011), Palermo (2016), Parma (2016), Reggio Emilia (2016), Rome (2011), Turin (2010). **Netherlands:** Rotterdam (2016), Utrecht (2015). **Portugal:** Lisbon (2011).
Congestion tolls	**Italy:** Milan (2008), Palermo (2016). **Sweden:** Gothenburg (2013), Stockholm (2007). **UK:** London (2003).

BSS	**Austria:** Vienna (2003). **Belgium:** Antwerp (2011), Brussels (2009). **Czech Republic:** Prague (2013). **Denmark:** Copenhagen (2014). **Finland:** Helsinki (2016). **France:** Avignon (2009), Bordeaux (2010), Grenoble (2011), Lille (2011), Lyon (2005), Marseille (2007), Montpelier (2007), Nantes (2008), Nice (2009), Paris (2007), Rennes (2009), Rouen (2007), Saint-Étienne (2010), Strasbourg (2010), Toulouse (2007). **Germany:** Berlin (2007), Bielefeld (2009), Bochum (2010), Cologne (2004), Dortmund (2010), Dresden (2007), Düsseldorf (2008), Duisburg (2010), Essen (2010), Frankfurt (2003), Hamburg (2009), Karlsruhe (2007), Leipzig (2005), Mannheim (2016), Munich (2001), Nuremberg (2011), Stuttgart (2007). **Greece:** Athens (2016), Thessaloniki (2013). **Hungary:** Budapest (2014). **Ireland:** Dublin (2009). **Italy:** Bari (2007), Brescia (2008), Cagliari (2010), Genoa (2009), Milan (2009), Modena (2014), Naples (2014), Padua (2013), Palermo (2016), Parma (2006), Reggio Emilia (2008), Rome (2008-2011), Torino (2010), Verona (2012). **Netherlands:** Utrecht (2016). **Poland:** Bydgoszcz (2015), Krakow (2008), Katowice (2015), Lodz (2016), Lublin (2014), Poznan (2012), Szczecin (2014), Warsaw (2012), Wroclaw (2011). **Romania:** Bucharest (2008). **Spain:** Alicante (2010), Barcelona (2004), Bilbao (2011), Córdoba (2007), Las Palmas (2011), Madrid (2014), Málaga (2013), Murcia (2015), Seville (2007), Valencia (2010), Valladolid (2013), Zaragoza (2011). **Sweden:** Gothenburg (2005), Stockholm (2006). **UK:** Belfast (2015), Bristol (2009-2010), Cardiff (2009-2011), Coventry (2015), Glasgow (2014), Liverpool (2014), London (2010), Newcastle (2011) , Nottingham (2013), Reading (2008-2011, 2014), Sheffield (2015).

Table 6: Descriptive statistics.

Variable	Mean	Standard deviation (all)	Standard deviation (between)	Standard deviation (within)
Congestion (%)	0.25	0.08	0.07	0.02
Tolls (dummy)	0.03	0.16	0.15	0.05
LEZ_general (dummy)	0.14	0.34	0.28	0.20
LEZ_trucks (dummy)	0.06	0.24	0.24	0.06
BSS (dummy)	0.48	0.50	0.39	0.31
Rail network (km)	21.94	51.55	51.62	3.23
Rail new (km)	1.87	5.37	4.66	2.69
Population (000)	1048.20	1459.63	1463.97	44.44
Density_region (inhabitants per square km)	1692.90	2343.04	2349.30	91.71
Density_main_city (% over population of urban area)	0.56	0.21	0.21	0.01
GDPpc (€)	29215.6	11101.06	10954.18	2015.06
Proportion new cars (%)	0.31	0.09	0.08	0.04

Table 7: VIF.

Explanatory variable	VIF
D^{Tolls}	1.49
$D^{LEZ\_general}$	1.16
D^{LEZ_trucks}	1.32
D^{BSS}	1.10
$Rail\_ntwk$	2.76
Pop	2.43
$Density\_region$	1.37
$Density\_main\_city$	1.18
$GDPpc$	1.72
$Prop\_new\_cars$	1.36

Table 8. Estimation results – pooled model.

	Dependent variable: $\log(Congestion)$
D^{Tolls}	0.24 (0.10)**
$D^{LEZ\_general}$	-0.05 (0.04)
D^{LEZ_trucks}	-0.08 (0.05)*
D^{BSS}	0.006 (0.03)
$Rail\_ntwk$	-0.001 (0.0006)**
$\log(Pop)$	0.28 (0.03)***
$\log(Density\_region)$	0.06 (0.01)***
$\log(Density\_main\_city)$	0.21 (0.05)***
$\log(GDPpc)$	-0.23 (0.07)***
$Intercept$	-1.15 (0.79)
City FE	NO
Year FE	YES
R^2	0.44
$Observations$	1162

Note: Standard errors in parentheses (clustered at the urban level).
Statistical significance at 1% (***), 5% (**), 10% (*).

Table 9. Estimation results – fixed effects model.

	Dependent variable: log($Congestion$)				
	(I)	(II)	(III)	(IV)	(V)
D^{Tolls}	-0.10 (0.03)***	-0.11 (0.03)***	-0.09 (0.03)**	-0.11 (0.04)**	-0.11 (0.03)***
$D^{LEZ\_general}$	0.05 (0.03)	0.04 (0.03)	-0.72 (0.88)	-0.18 (0.08)**	0.05 (0.04)
D^{LEZ_trucks}	0.007 (0.02)	0.009 (0.02)	0.009 (0.02)	0.01 (0.02)	0.02 (0.03)
D^{BSS}	-0.03 (0.01)*	-0.03 (0.01)*	-0.03 (0.01)*	-0.03 (0.01)*	0.01 (0.02)
$Rail\_ntwk$	-0.002 (0.001)	–	-0.002 (0.001)	-0.001 (0.001)	0.0008 (0.001)
$Rail\_new$	–	-0.004 (0.001)*	–	–	–
$D^{LEZ\_general}x\log(GDPpc)$	–	–	0.07 (0.08)	–	–
$D^{LEZ\_general}xProp\_new\_cars$	–	–	–	0.71 (0.31)**	–
$Prop\_new\_cars$	–	–	–	0.42 (0.26)	–
log(Pop)	1.36 (0.43)***	1.42 (0.43)***	1.32 (0.43)***	1.40 (0.46)***	1.70 (0.72)**
log($Density\_region$)	0.18 (0.23)	0.16 (0.22)	0.17 (0.23)	0.10 (0.22)	0.25 (0.47)
log($Density\_main\_city$)	0.13 (0.10)	0.12 (0.10)	0.13 (0.10)	0.09 (0.11)	0.09 (0.18)
log($GDPpc$)	0.35 (0.18)*	0.34 (0.19)*	0.33 (0.19)*	0.17 (0.20)	0.80 (0.25)***
$Intercept$	-14.95 (3.63)***	-15.14 (3.58)***	-14.49 (3.67)***	-13.03 (3.64)***	-22.77 (5.14)***
City FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Sample	All	All	All	All	Matching
R^2	0.24	0.23	0.24	0.22	0.24
$Observations$	1162	1162	1162	1139	474

Note: Standard errors in parentheses (clustered at the urban level).
Statistical significance at 1% (***), 5% (**), 10% (*).

Figures

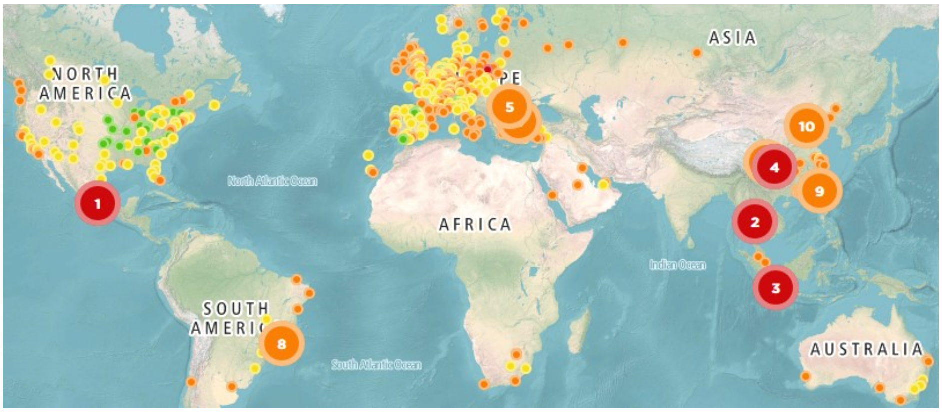

Figure 1: Map with the most congested cities in the world.

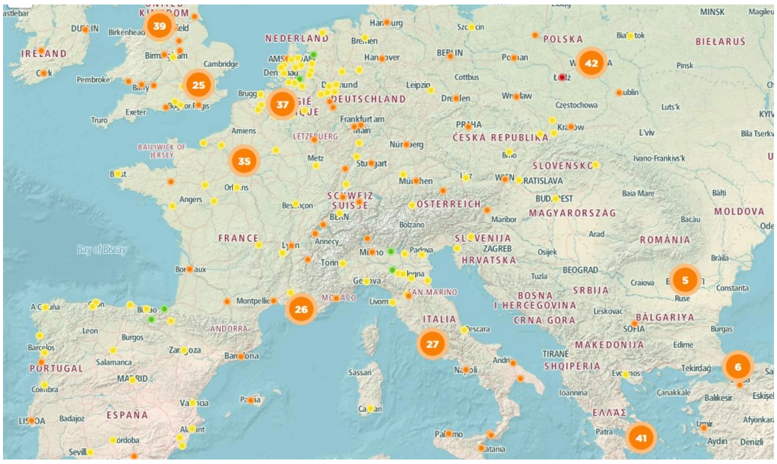

Figure 2: Map with the most congested cities in Europe.

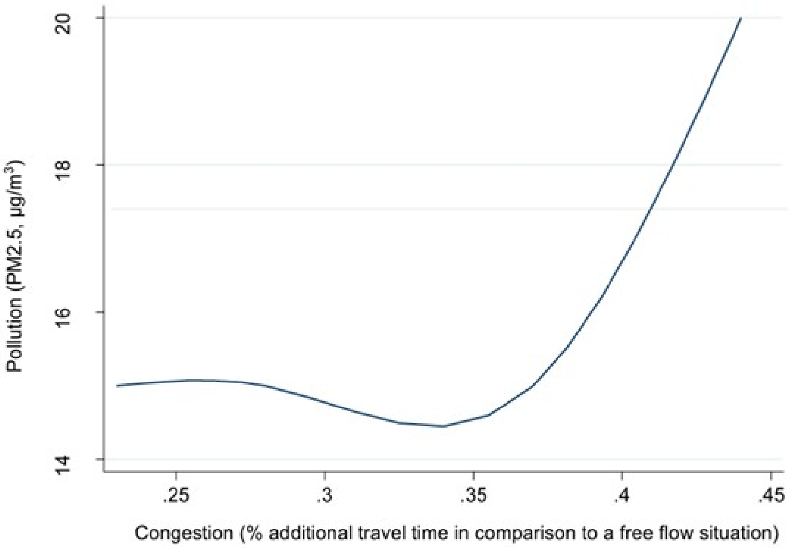

Figure 3: Median spline between pollution and congestion.
(European cities in our sample for 2016)

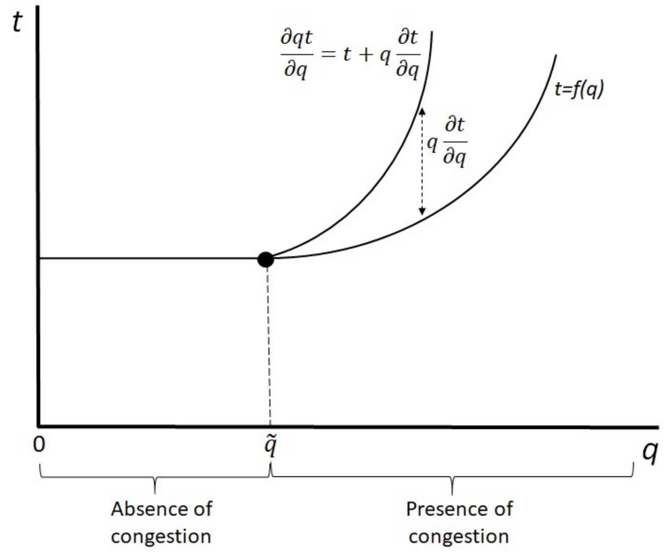

Figure 4: Congestion as a negative externality.

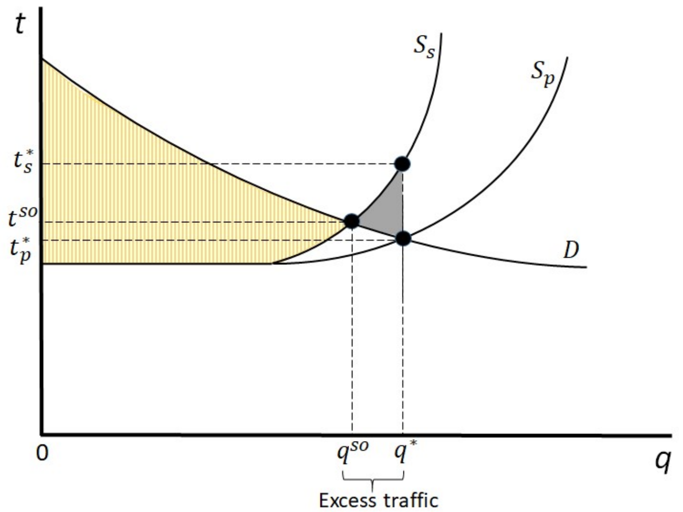

Figure 5: The equilibrium and the social optimum.

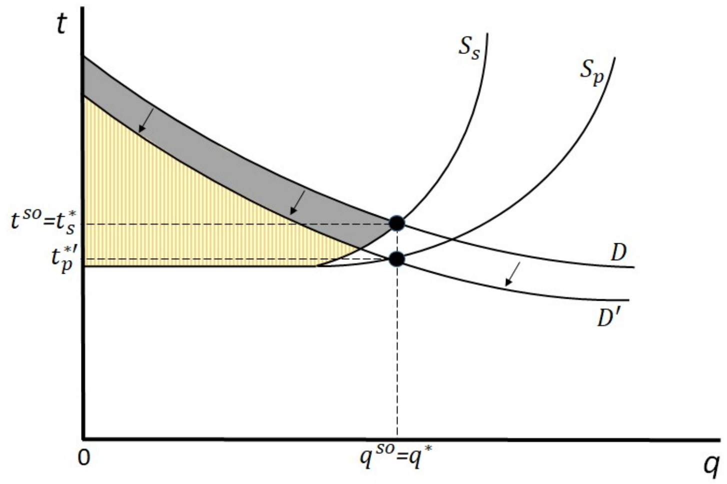

Figure 6: Quantity measures.

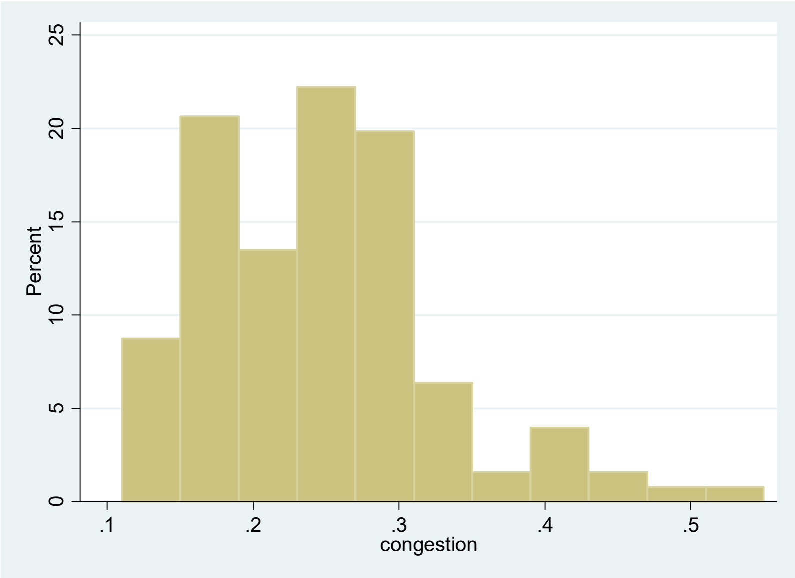

Figure 7: Histogram of the congestion variable in 2008.
(% additional travel time in comparison to a free flow situation)

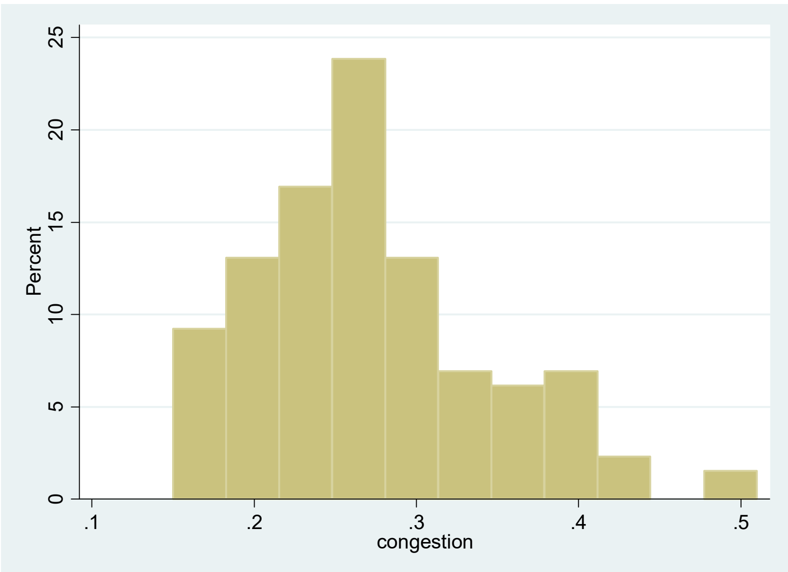

Figure 8: Histogram of the congestion variable in 2016.
(% additional travel time in comparison to a free flow situation)

Appendix

Table A1. P-score matching estimation (logit).

	Dependent variable: $D^{LEZ\_general}$
$\log(Congestion)$	-2.05 (1.07)*
$Rail\_ntwk$	-0.02 (0.008)***
$Prop\_new\_cars$	-7.60 (3.06)***
$\log(Pop)$	0.67 (0.54)
$\log(Density\_region)$	0.47 (0.21)**
$\log(Density\_main\_city)$	0.71 (0.73)
$\log(GDPpc)$	3.74 (0.97)***
$Intercept$	-46.54 (10.66)***
R^2	0.24
$Observations$	125

Note: Standard errors in parentheses (clustered at the urban level).
Statistical significance at 1% (***), 5% (**), 10% (*).

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