Mitigating congestion in urban areas: Urban tolls versus low emission zones*

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Abstract

The intensive use of private transportation in urban areas generates congestion and pollution, two externalities that are clearly related as prolonged car circulation at reduced speeds has a notable effect on the emission of polluting substances. This paper compares the effectiveness of low emission zones (LEZ) and urban tolls in mitigating congestion for a sample of European urban areas over the period 2008-2019. Our main finding consists in showing that urban tolls are more effective than LEZ in reducing congestion. An explanation could come from the fact that tolls are usually accompanied by public transportation improvements. Furthermore, LEZ may spur the renewal of the car fleet, so that older and more polluting cars are replaced by new and cleaner cars. Hence, LEZ may only have a short-term effect in terms of reducing congestion. Finally, LEZ cities are relatively rich so that their inhabitants may be financially capable of renewing their vehicles to overcome the restriction imposed by this policy. Even though urban tolls are more effective in reducing congestion than LEZ, we observe that tolls are rarely implemented whereas LEZ are increasingly adopted in many European cities. The ultimate reason explaining this policy choice has to do with the fact that LEZ are much better accepted that urban tolls. We also provide some guidelines to better understand this phenomenon.

Keywords: Pollution, congestion, low emission zones, urban tolls, urban areas.

1. INTRODUCTION

The intensive use of private transportation in urban areas generates congestion and pollution, two externalities that are clearly related as prolonged car

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circulation at reduced speeds has a notable effect on the emission of polluting substances (Barth and Boriboonsomsin, 2008; Beaudoin, Farzin and Lin Lawell, 2015; Parry, Walls and Harrington, 2007).

In particular, the problem of urban congestion is explained by the fact that supply (infrastructure) is unable to absorb demand, especially during peak hours. Urban congestion produces traffic jams producing high socio-economic costs. 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 exhibit could reach $300 billion by 2030.[1] Focusing on Spanish cities, TomTom has elaborated a report concluding that national firms lose more than €840 million per year due to traffic jams (data from 2016).[2] It is worth noting the size of the average per-commuter yearly loss in the two largest Spanish cities: 119 overtime hours behind the wheel in the case of Barcelona (equivalent to 14 working days) and 105 in the case of Madrid. This time translates into a huge economic loss of €175.5 million in Barcelona and €187.5 million in Madrid.

As for polluting emissions, they 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) 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 every year (2012 estimate).

Investments in capacity are extremely expensive, involve long gestation periods, and are not effective in urban areas with dense road networks.[3] Therefore, two

1 Information from *The Economist* (2014).

2 https://telematics.tomtom.com/es_es/webfleet/blog/coste-los-atascos-las-empresas/

3 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.

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.[4] 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 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.

In this paper, we compare the effectiveness of LEZ and urban tolls in mitigating congestion for a sample of European urban areas. More precisely, we explore the evolution of congestion in each city having implemented LEZ and/or tolls in comparison to cities that have not implemented any of these policies (*i.e.*, control cities). For each treated city, we compare the evolution of congestion from the year before implementation until the last year with available data.

Our sample contains information for 130 cities with a population exceeding 300,000 inhabitants from 19 different European countries over the period 2008-2019. There are 45 cities from 12 countries having implemented a LEZ in the considered period (LEZ are massively implemented in German and Italian cities). Instead, urban tolls have only been implemented in five European cities: London (2003), Stockholm (2007), Milan (2008), Gothenburg (2013), and Palermo (2016). Furthermore, urban tolls are combined with LEZ in Milan and Palermo. All in all, it is clear that LEZ are more widely applied than tolls: while there is an extensive use of LEZ across European cities, very few cities have applied urban tolls.

Focusing on European urban areas, some previous studies have studied the effectiveness of urban tolls in mitigating congestion in Stockholm (Eliasson, 2008; Börjesson *et al.*, 2012; Börjesson, Brundell-Freij and Eliasson, 2014), London (Santos and Fraser, 2006) Milan (Gibson and Carnovale, 2015; Rotaris *et al.*, 2010; Percoco, 2013), and Gothenburg (Andersson and Nässén, 2016). All

4 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).

these studies conclude that urban tolls are effective in reducing congestion from the first year of implementation. As for LEZ, the only study that has examined their impact on congestion is Bernardo, Fageda and Flores-Fillol (2020) and they conclude that, on average, LEZ are ineffective in reducing congestion.

Our main finding consists in showing that urban tolls are more effective than LEZ in reducing congestion. An explanation could come from the fact that tolls are usually accompanied by public transportation improvements while this is not usually the case for LEZ. Furthermore, LEZ may spur the renewal of the car fleet, so that older and more polluting cars are replaced by new and cleaner cars. Hence, LEZ may have positive effects in terms of pollution but not in terms of congestion. In this regard, our data suggests that LEZ may have a short-term effect in terms of reducing congestion but we do not find evidence of positive effects in the long-term for most cities in our sample. Finally, LEZ cities are relatively rich so that their inhabitants may be financially capable of renewing their vehicles to overcome the restriction imposed by this policy. In this vein, we find a stronger impact of LEZ on congestion in cities that are relatively poor in the context of our data, such as Naples or Lisbon.

The rest of the paper is organized as follows. Section 2 describes the way congestion is measured in our analysis. In Section 3 we present the current application of LEZ and urban tolls in European cities. Section 4 studies the effectiveness of LEZ and urban tolls in mitigating congestion. Finally, Section 5 offers some final considerations based on the differences between LEZ and urban tolls in terms of acceptability.

2. MEASURE OF CONGESTION

Our sample contains information from urban areas in the European Union and United Kingdom with a population exceeding 300,000 inhabitants over the period 2008-2019. The sample of cities is determined by the availability of congestion data. Our sample has information for 130 cities from 19 different countries.

The indicator of congestion 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.[5] 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.[6] 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.

A 40% congestion level, for example, means that a 30-minute trip will take 40% more time that it would take during uncongested conditions. For this 30-minute trip, the extra travel time is about 12 minutes. Note here that our congestion data is an average of all trips across the whole day. In peak periods, the extra travel time may be close to 100% in the most congested cities.

Exhibits 1 and 2 provide information about the magnitude of the problem that congestion represents for cities in our sample. In terms of the congestion indicator that we use, a high proportion of cities in our sample lie in the range that goes from 20% to 40% excess travel time, although cities with congestion records higher than 50% can also be identified (Bucharest, Kraków, Dublin), as well as and cities with congestion records around 10% (Brescia, Karlsruhe, Tampere).

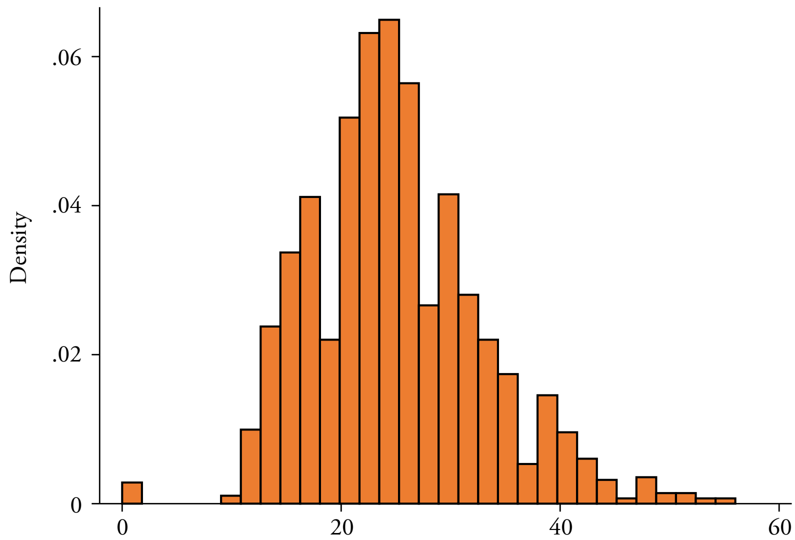
From a general perspective, the levels of congestion can be considered as relatively high for a large number of cities in our sample. Furthermore, Exhibit 2 reveals that congestion is worsening in the considered period. The mean level of congestion in cities of our sample was about 23% in 2008 while it reaches 27% in 2019. Although we can see some fluctuations in the annual evolution of congestion, there is a clear increasing trend in congestion records for cities in our sample.

5 https://www.tomtom.com/en_gb/trafficindex

6 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.

Exhibit 1

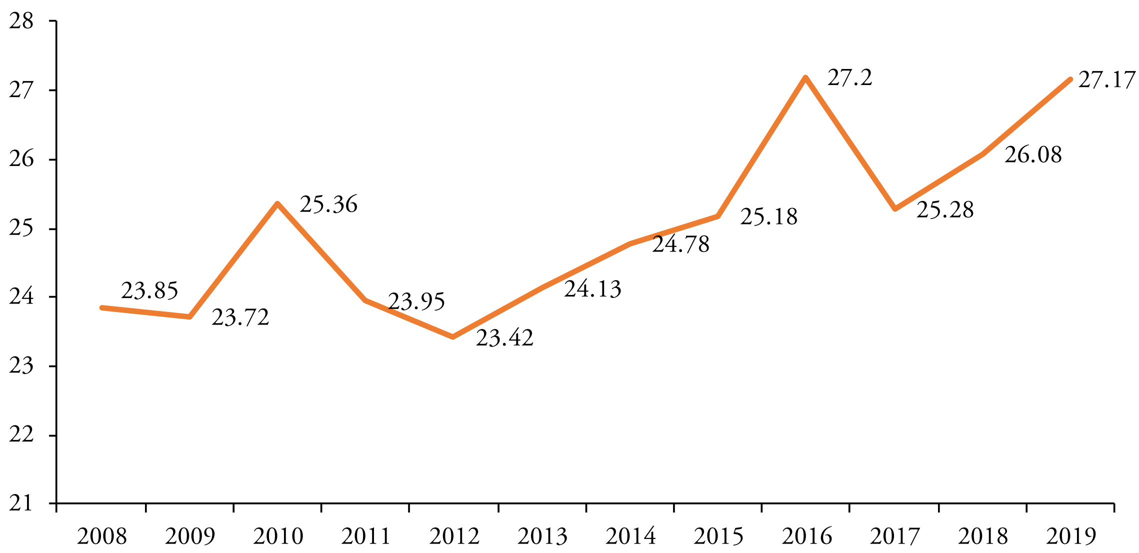
Histogram of the congestion variable



Source: Own elaboration.

Exhibit 2

Evolution of congestion for cities in our sample



Source: Own elaboration.

3. LEZ AND URBAN TOLLS IN EUROPEAN CITIES

Data about the implementation of LEZ and toll policies have been obtained from CLARS (Charging, Low Emission Zones, other Access Regulation Schemes), a website promoted by the European Commission and built by Sadler Consultants Ltd.[7] These data are complemented with city regulations searched online.

Table 1 shows the cities in our sample having applied LEZ for all types of vehicles in the considered period: 45 cities from 12 countries. Most of large cities in Western and Northern Europe have implemented a LEZ in the considered period.[8] The decision and implementation of LEZ corresponds ultimately to city councils (type of vehicles restricted, emission standards, boundaries, fines).[9] However, some underlying national dynamics remain important, as LEZ are massively implemented in German and Italian cities, while they are occasionally implemented in French, British or Spanish cities (being the only cases Paris, London, Madrid, and Barcelona) and in Eastern Europe metropolises (Prague and Kraków).

There may be some heterogeneity in the application of LEZ. Some of the first LEZ in Germany and Italy only ban diesel cars but the emission standards in recent years for almost all cities affects diesel and petrol cars. The most common emission standard, particularly in German cities, is Euro 4 for Diesel cars and Euro 1 for petrol cars. However, several cities impose tighter requirements. Only few cities like Rotterdam, Utrecht or Athens ban just diesel cars. Furthermore, most of cities restrict the city center although obviously the size of the restricted area varies across cities. In this regard, a few cases restrict most of the city like Barcelona, Paris, Rome or Milan although it is usual to set tighter requirements in the city center.

7 http://urbanaccessregulations.eu

8 However, LEZ only applies to specific vehicles like trucks, vans and/or buses in some cases. Note that our focus here is on LEZ applied to all type of vehicles including passenger cars.

9 Although national frameworks may set some rules, such as the classification of vehicles used in environmental labels.

Table 1
LEZ cities in our sample

Country (# LEZ cities)	City	Starting year	# non-LEZ cities
Belgium (3)	Antwerp	2017	2
	Brussels	2019	
	Ghent	2020	
Czech Republic (1)	Prague	2016	1
Germany (19)	Berlin	2008	3
	Bochum	2013	
	Bonn	2010	
	Bremen	2010	
	Cologne	2013	
	Dortmund	2013	
	Düsseldorf	2009	
	Duisburg	2013	
	Essen	2013	
	Frankfurt	2010	
	Hamburg	2018	
	Hannover	2010	
	Karlsruhe	2013	
	Leipzig	2011	
	Mannheim	2013	
	Münster	2010	
	Munich	2012	
	Stuttgart	2010	
	Wuppertal	2011	
France (1)	Paris	2017	16
Greece (1)	Athens	2018	1

Table 1 (continued)

LEZ cities in our sample

Country (# LEZ cities)	City	Starting year	# non-LEZ cities
Italy (13)	Brescia	2019	6
	Bologna	2016	
	Florence	2008	
	Genoa	2016	
	Milan	2008	
	Modena	2016	
	Naples	2011	
	Palermo	2016	
	Parma	2016	
	Reggio Emilia	2016	
	Rome	2011	
	Turin	2010	
	Verona	2018	
The Netherlands (2)	Rotterdam	2016	3
	Utrecht	2015	
Poland (1)	Kraków	2019	9
Portugal (1)	Lisbon	2011	1
Spain (1)	Barcelona	2020	11
	Madrid	2018	
Sweden (1)	Stockholm	2020	1
United Kingdom (1)	London	2019	22

Notes: Other non-LEZ cities in our sample: Tampere and Helsinki (Finland), Budapest (Hungary), Bucharest (Romania), Bratislava (Slovakia), and Dublin (Ireland). LEZ for specific vehicles: Glasgow and Brighton (buses), Lyon and Grenoble (trucks and vans), Amsterdam, Copenhagen, Helsinki and Gothenburg (trucks and buses), Vienna, Eindhoven, and The Hague (trucks). Emergency-LEZ: Lille, Marseille, Strasbourg and Toulouse. Plans for LEZ for all vehicles in several cities in the UK and The Netherlands.

Source: Own elaboration.

Table 2
Toll cities in our sample

City	Starting year
London	2003
Stockholm	2006
Milan	2008
Gothenburg	2013
Palermo	2016

Note: Unsuccessful plans for urban tolls have been observed in Copenhagen, Edinburgh, Manchester, and Helsinki.

Source: Own elaboration.

Table 2 shows the cities in our sample having applied a congestion charge scheme in the considered period. Only five cities have implemented it and, in two of them (Milan and Palermo), they are combined with LEZ.[10] Out of our sample, tolls have only been applied in Singapore and some Norwegian cities (Oslo, Bergen, and Trondheim).

All in all, it is clear that LEZ are more widely applied than tolls: while there is an extensive use of LEZ across European cities, very few cities have applied urban tolls.

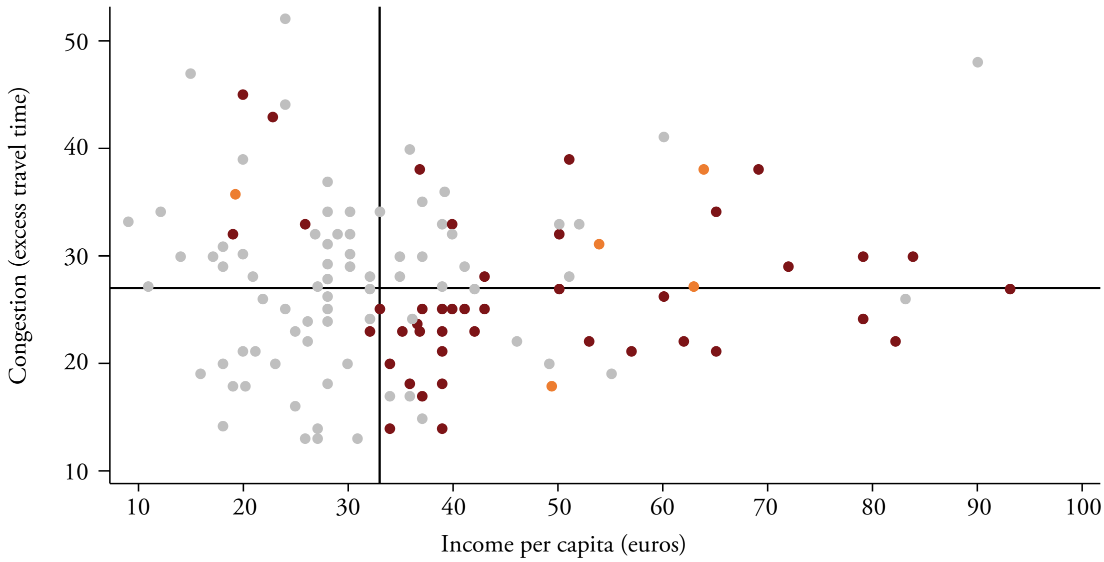
A priori, we should expect LEZ to be mainly applied in highly polluted cities, given that their main goal is to fight against the emission of local pollutants by cars. However, Fageda, Flores-Fillol and Theilen (2020) show that the main driver in the implementation of LEZ is urban income. Since our interest here is on the link between congestion and LEZ/toll policies, Exhibit 3 explores whether these policies are mostly applied in highly congested cities.

There are only four LEZ cities with an income clearly below the sample median (Athens, Kraków, Napoles, and Lisbon) and two additional LEZ cities with an income slightly below the sample median (Bochum, Turin). Finally, Palermo (that

10 Urban tolls are also applied in Durham (2002) or Valletta (2007) but they affect a few streets in the historic center of these small cities. They are also applied in several cities in Norway but their primary purpose is to collect funds for road investments (Larsen and Østmoe, 2001). The only relevant case of urban tolls not included in our sample is Singapore (1975).

Exhibit 3

Range scatter plot of congestion vs. income in 2019



Note: Brown dots denote LEZ cities, orange dots toll cities, and grey dots cities with no LEZ or tolls.

Source: Own elaboration.

applies a combination of LEZ and tolls) has also an income below the median. All these *relatively poor* LEZ cities have congestion records higher than the median. The rest of cities with an income below the median (58 cities) are non-LEZ cities, regardless their congestion records. In fact, these non-LEZ cities include many highly congested cities in Eastern Europe. Instead, there are 38 LEZ cities (out of 65 cities) with urban incomes higher than the median. Only 11 of these 38 *relatively rich* LEZ cities have congestion records higher than the median, including cities such as Brussels, London, Milan (that applies a combination of LEZ and tolls), Paris, Rome, and several German cities. Therefore, we confirm the key role of urban income in the adoption of LEZ described in Fageda, Flores-Fillol and Theilen (2020).

Regarding toll cities, only Palermo has an income lower than the median. Thus, the acceptability of this policy seems also to be conditioned by urban income. However, the existing literature (see below) shows that an additional driver in the implementation of this policy has been the magnitude of the car-related externalities (the only toll city with congestion records lower than the mean sample is Gothenburg). At this point, it is useful to briefly review the studies that analyze the origin of urban tolls in London, Stockholm, Milan, and Gothenburg.

- *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).

- *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 pricing scheme (Eliasson and Johnson, 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).

- *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 low emission zone*: 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, 2013). 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 low emission zone*: 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 5.1µg/m^3 (being our sample mean 14.82µg/m^3). The main purpose of the urban toll in this case was to co-fund investments in transportation infrastructures (Andersson and Nässen, 2016; Börjesson and Kristoffersson, 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 low emission zone: 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.

4. EFFECTIVENESS OF LEZ AND TOLLS IN MITIGATING CONGESTION

Previous studies for German cities suggest that LEZ can be effective in improving air quality (Malina and Scheffler, 2015; Wolff, 2014; Morfeld, Groneberg and Spallek, 2014). Studies for other specific European cities also find similar qualitative results: Amsterdam (Panteliadis *et al*., 2014), London (Ellison, Greaves and Hensher, 2013), and Rome (Cesaroni *et al.*, 2012). However, the impacts vary according to the pollutant examined, with stronger effects for PM10 and more modest outcomes for NO, NO, NO_2, and NOx. The effectiveness of LEZ in mitigating congestion is less clear. The only study that has examined the impact of LEZ on congestion is Bernardo, Fageda and Flores-Fillol (2020) and they conclude that, on average, LEZ are ineffective in reducing congestion.

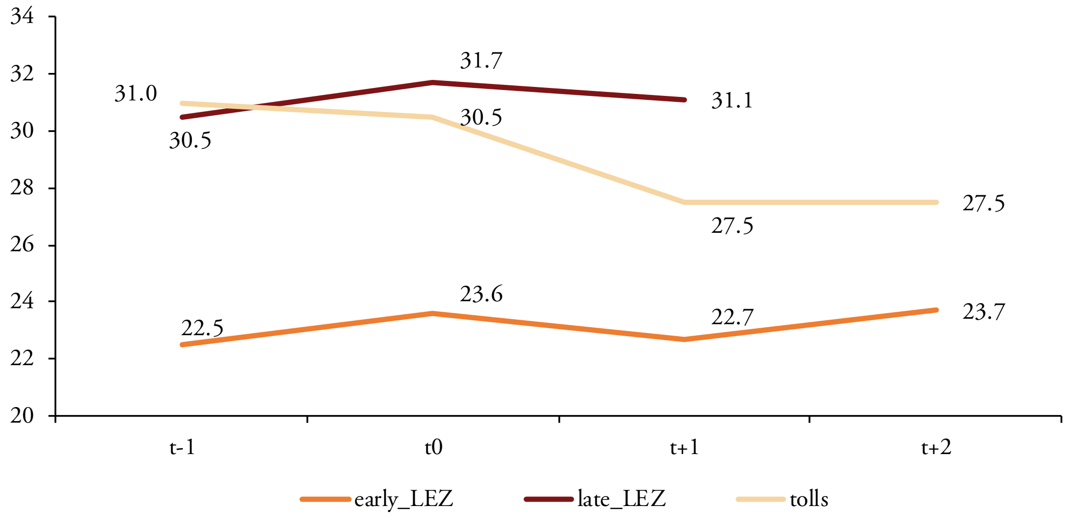
By contrast, there is extensive evidence on the effectiveness of urban tolls in mitigating congestion. Indeed, several previous studies have examined their impact on individual cities by comparing either traffic or congestion levels before and after their implementation. All of them find urban tolls 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; Börjesson, Brundell-Freij and Eliasson, 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). In Singapore, their effectiveness has been shown to be even higher as compared to European cities (Phang and Toh, 1997; Willoughby, 2000; Olszewski and Xie, 2005). 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 London (Green, Heywood and Navarro 2016), and in terms of children health in Stockholm (Simeonova *et al.*, 2019).

Focusing on every city in our sample having implemented either LEZ or urban tolls (or both of them), we explore the effectiveness of these policy measures in mitigating congestion.

Exhibit 4 shows the short-term evolution of congestion in treated cities (*i.e.*, cities that have applied LEZ and/or urban tolls). This exhibit is centered on the implementation year of the policy and shows the evolution of congestion one year before and two years after (one year after for late LEZ cities). Therefore, we build two different groups of LEZ cities based on the year of the implementation

Exhibit 4

Short-term evolution of congestion (% extra-travel time as compared to free-flow conditions) in cities applying LEZ and/or urban tolls



Source: Own elaboration.

of the policy: early LEZ cities (having implemented the policy before 2017) and late LEZ cities (having implemented it from 2017 onward). For both groups of LEZ cities, a slight decrease in congestion is observed during the year after the implementation of the policy (such effect is totally diluted during the second post-implementation year of the policy for early LEZ cities). For toll cities, we can only examine the effects over time for Gothenburg and Palermo, given that only these two cities applied their urban tolls after 2008. For these two toll cities, there is a strong decrease in congestion after the first post- implementation year. The lower levels of congestion are maintained during the second post-implementation year.

Data in this exhibit evoke that LEZ may not be effective in containing congestion. Instead, we confirm the results from previous studies suggesting a clear effect of tolls in mitigating congestion.

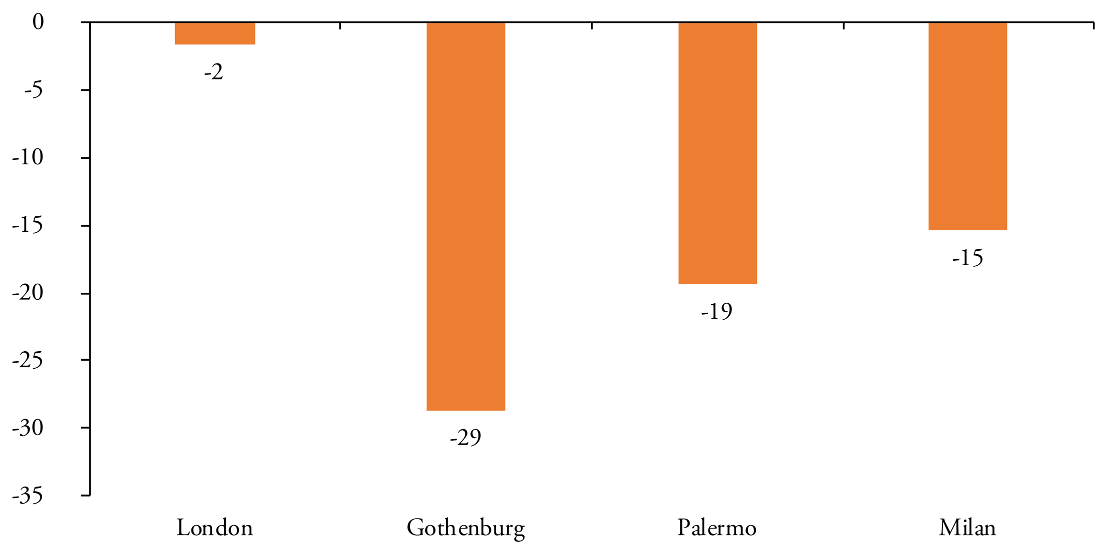
Taking this into account, the exhibits that follow explore the evolution of congestion in each city having implemented LEZ and/or tolls in comparison to cities that have not implemented any of these policies (*i.e.*, control cities).

For each treated city, we compare the evolution of congestion from the year before implementation until the last year with available data. For example, given that the year before implementation of urban tolls in Gothenburg was 2013, we therefore analyze the evolution of congestion in Gothenburg as compared to the group of control cities over the period 2012-2019. Similarly, given that the year before implementation of LEZ in Prague was 2016, we therefore analyze the evolution of congestion in Prague as compared to the group of control cities over the period 2015-2019.

Exhibit 5 provides these numbers for cities having applied either tolls or a combination of tolls and LEZ. Our considered period 2008-2019 implies some limitations: i) as London applied tolls in 2003, we can only examine the effect of LEZ implemented in 2018; ii) as tolls in Milan were applied in 2008, we can only examine the evolution of congestion since the implementation year (and not since the year before implementation); and iii) as tolls in Stockholm were applied in 2007, we need to exclude this city from our analysis.

Exhibit 5

Evolution of congestion in toll cities or combined tolls/LEZ versus control cities since the year before implementation



Source: Own elaboration.

A remarkable reduction in congestion as compared to control cities is observed in the two cities where we can properly identify the effects before and after the implementation of tolls (Gothenburg and Palermo). Such reduction is about 29% in Gothenburg and 19% in Palermo. There is a remarkable mitigation of congestion in Milan as well (15%), a number that may be underestimated due to the lack of information of the year before implementation. Finally, the application of LEZ in London, a city that had previously introduced an urban toll in 2003, does not seem to be successful in promoting further reductions in congestion.

With respect to the aforementioned effectiveness of urban tolls in mitigating congestion, a caveat needs to be made. As toll revenues are typically used to improve public transit, it is complicated to distinguish between the direct effects of tolls and the indirect effects derived from these improvements of public transit.

Exhibits 6, 7, and 8 replicate the analysis for LEZ. Given the high number of LEZ cities in our sample, we can classify them into three groups: i) German LEZ cities (Exhibit 6); ii) Italian LEZ cities (Exhibit 7); and iii) LEZ cities from other European countries (Exhibit 8).

Exhibit 6 shows a high heterogeneity in the evolution of congestion in German LEZ cities as compared to control cities, with a prevalence of LEZ cities experiencing increased congestion records.

Cologne, Leipzig, Mannheim, Wuppertal and, to a lower extent, Hamburg, are the only German LEZ cities performing better than the group of control cities. We can provide some explanations for this observed fact. In Cologne and Leipzig, this differential effect could be related to having larger restricted areas (part of the city center affected by LEZ). In addition, Leipzig and Mannheim banned older and more polluting diesel vehicles (those with yellow and red stickers) before the rest of German cities (in 2011 and 2013, respectively). Furthermore, we need to take into account that the evolution of congestion in Exhibit 6 makes reference to a relatively long post-treatment period, as most German LEZ cities implemented the

Exhibit 6

Evolution of congestion in German LEZ cities versus control cities since the year before implementation

(Percentage)

Source: Own elaboration.

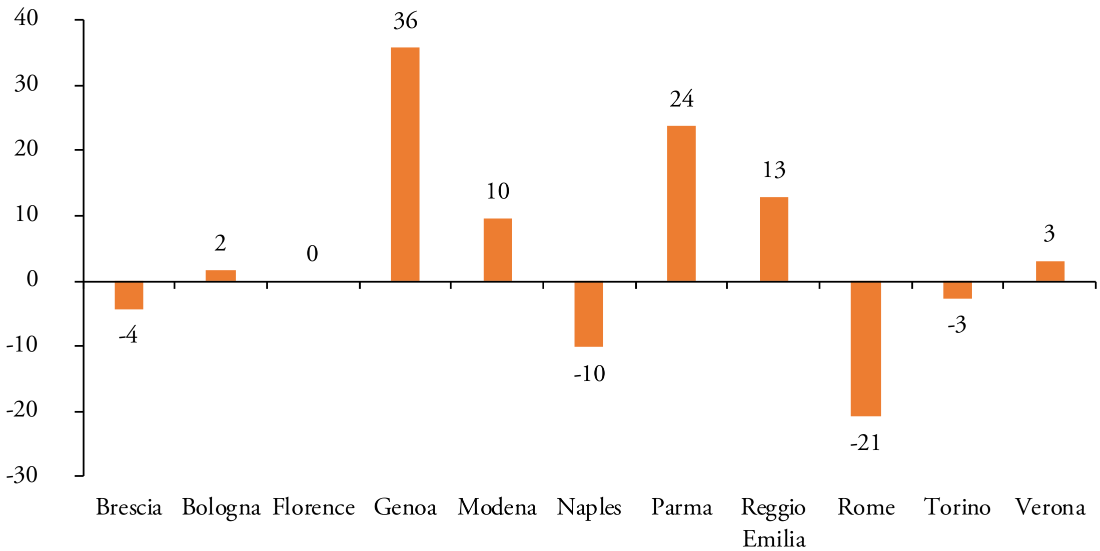
policy many years ago (being Hamburg the main exception). Finally, urban income in Cologne, Leipzig, and Wuppertal is lower than the average for German cities. In general, German cities are relatively rich and it is sensible to consider a lower effectiveness of LEZ in containing congestion in high-income urban areas.

Exhibit 7 shows a similar pattern for Italian LEZ cities, as most of them experienced increased congestion records. The exceptions are Naples and Rome and, to a lower extent, Brescia and Turin. We can provide some explanations for this observed fact. In the case of Brescia, only the short-term effects can be examined as it applied the policy in 2019. Naples is one of the few LEZ cities in our sample that is relatively poor and Turin is not particularly rich either. Rome is one of the few cities in our sample where LEZ being applied to the entire city. Besides, there is probably an effect coming from the relevant metro expansion carried out in Rome during 2014.

Exhibit 7

Evolution of congestion in Italian LEZ cities versus control cities since the year before implementation

(Percentage)



Source: Own elaboration.

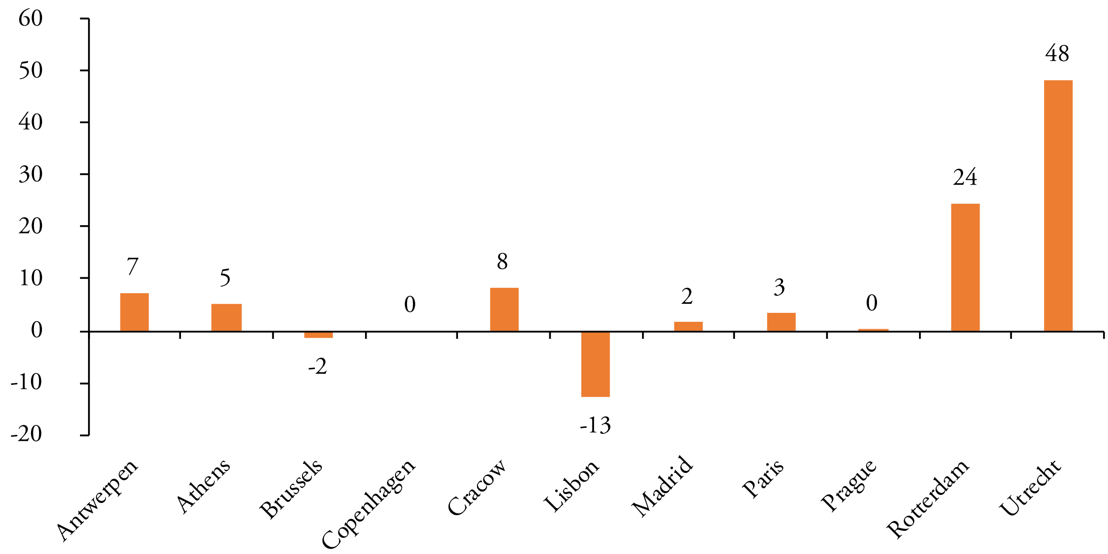
Finally, Exhibit 8 shows again a similar behavior in LEZ cities outside Germany and Italy, *i.e.*, a high heterogeneity and a general bad performance of LEZ. The only exceptions are: i) Brussels, where the policy was applied in 2019; and ii) Lisbon, which is one of the few relatively poor LEZ cities in the context of our data.

To sum up, we conclude that urban tolls are more effective than LEZ in reducing congestion. An explanation could come from the fact that tolls are usually accompanied by public transportation improvements while this is not usually the case for LEZ. Furthermore, LEZ may spur the renewal of the car fleet, so that older and more polluting cars are replaced by new and cleaner cars. Hence, LEZ may have positive effects in terms of pollution but not in terms of congestion. In this regard, our data suggests that LEZ may have a short-term effect in terms of reducing congestion but we do not find evidence of positive effects in the long-term for most cities in our sample. Finally, LEZ cities are relatively rich so that their inhabitants may be financially capable of renewing their vehicles to

Exhibit 8

Evolution of congestion in non-German and non-Italian LEZ cities versus control cities since the year before implementation

(Percentage)



Source: Own elaboration.

overcome the restriction imposed by this policy. In this vein, we find a stronger impact of LEZ on congestion in cities that are relatively poor in the context of our data, such as Naples or Lisbon.

5. DISCUSSION ON THE ACCEPTABILITY OF URBAN TOLLS AND LEZ

As pointed out above, the main lesson that can be derived from our analysis is that urban tolls are more effective in reducing congestion than LEZ. Instead, we observe that urban tolls are rarely implemented whereas LEZ are increasingly adopted in many European cities. The ultimate reason explaining this policy choice has to do with the fact that LEZ are much better accepted that urban tolls. In this section, we provide some guidelines to better understand this issue (for a thorough analysis on the acceptability of price and quantity restrictions, see Fageda, Flores-Fillol and Theilen, 2020).

There is a prevalence of quantity over price measures with quantity measures being applied in high-income cities. There are a number of reasons explaining this statement. First, even though both price measures (*i.e*., urban tolls) and quantity measures (*i.e.,* LEZ) are potentially equivalent instruments to mitigate pollution and congestion simultaneously, there is a general perception that i) pollution is a more severe externality, and ii) quantity measures are more effective in curbing pollution.[11] Second, quantity restrictions only ban specific vehicles (the most polluting ones), thereby affecting a limited number of commuters (while tolls affect every commuter). As a consequence, the acceptability of quantity measures can be easily enhanced by relaxing their stringency. Third, quantity measures are very cheap to implement by city councils as they are not expected to be accompanied with investments in public transportation. Fourth, quantity measures spur the renewal of the car fleet as a fraction of older and more polluting cars are replaced by new and cleaner cars. These measures 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.

Departing from these reasons, Fageda, Flores-Fillol and Theilen (2020) conclude that having a majority of commuters that remain commuting after the policy is implemented is the key element for the prevalence of quantity measures, which are easier to implement and benefit high-income commuters who own the newer and less polluting cars.

Trial periods are used to enhance the acceptability of urban tolls before their permanent implementation (Stockholm and Milan), but not in the case of quantity measures. The relevance of reducing individual uncertainty to overcome the resistance to urban tolls has been explained in De Borger and Proost (2012), who consider that initial drivers are uncertain about their situation after the implementation of urban tolls as they do not know exactly whether they will remain commuting (becoming remaining drivers) or stop driving (becoming ex-drivers). Therefore, *ex ante*, initial drivers are unsure about their willingness to pay. De Borger and Proost (2012) show that initial drivers underestimate the positive effects of urban

11 Posada *et al.* (2015) suggest that quantity instruments can be very effective in curbing pollution.

tolls, meaning that a larger fraction would oppose *ex ante* than *ex post* (once the uncertainty is resolved). This result would help explaining the small number of successful experiences in implementing urban tolls, along with the resistance and failure to apply them in many cities such as Copenhagen, Edinburgh, Manchester, Helsinki, New York or Hong Kong.

Fageda, Flores-Fillol and Theilen (2020) conclude that commuters are overoptimistic about the effects of quantity measures and overpessimistic about those of price measures. As a consequence, a successful introduction of urban tolls benefits from trial periods that help dispelling this uncertainty. By contrast, trials would undermine the acceptability of quantity-based measures.

Some cities use of a combination of price and quantity measures (Milan and Palermo) while others are embroiled in long-lasting discussions without applying any measure. More precisely, Milan and Palermo designed a combination of price and quantity measures while London, Stockholm, and Gothenburg started with a congestion charge scheme and adopted LEZ later on. In Gothenburg, the low emission zone is restricted to trucks and buses. Therefore, a combination of price and quantity measures can be deemed as a more popular policy as compared to a rise of existing tolls. On the long-lasting discussions on the most convenient measure to be applied, we could refer to the experience of Barcelona where a debate started around 2005 and lasted until the approval of a low emission zone in 2019. From this moment and despite the adopted decision, the issue is still far from being settled and there is an ongoing discussion on the possibility to modify the current low emission zone to combine it with an urban toll (as in the case of Milan and London). The resistance to any policy reform can give clues to these long-lasting discussions that delay the application of any measure in several cities.

Using a model with peak and off-peak periods, Fageda, Flores-Fillol and Theilen (2020) conclude that a majority of citizens prefers a combination of price and quantity measures over an exclusive implementation of either tolls or quantity restrictions under some realistic and mild conditions (having congestion concentrated in peak periods and a sufficiently large number of remaining peak drivers once the policy is implemented). They also show that having to choose among several traffic restrictions can result into voting cycles, *i.e.*, a lack of consensus resulting into long-lasting policy discussions that end up delaying the actual implementation of any measure.

Policy makers commit to invest in public transit to enhance the acceptability of urban tolls (London, Stockholm, Milan, Gothenburg, and Palermo), but not in the case of quantity measures. Several authors have emphasized the importance of credible commitments in enhancing the acceptability of urban tolls. Their main conclusion is that, in order to receive social support, urban tolls require to be accompanied by important investments in public transportation and/or the reduction of other taxes (a detailed revision of this literature is provided in De Borger and Proost, 2012).

Fageda, Flores-Fillol and Theilen (2020) confirm that using toll revenues to subsidize public transit enhances the acceptability of tolls, but they also observe that high-income commuters (who own the newer and less polluting cars) still prefer quantity restrictions as they gain from pollution and congestion mitigation at no cost.

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