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Price versus quantity measures to deal with pollution and congestion in urban areas: A political economy approach[☆]

Xavier Fageda[a], Ricardo Flores-Fillol[b,*], Bernd Theilen[b]

[a] Department of Economic Policy, Universitat de Barcelona, Avinguda Diagonal 690, 08034 Barcelona, Spain
[b] Departament d'Economia and ECO-SOS, Universitat Rovira i Virgili, Avinguda de la Universitat 1, 43204 Reus, Spain

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ABSTRACT

Pollution and congestion in urban areas are serious externalities that can be mitigated through the adoption of either price- or quantity-based mechanisms. While price restrictions are occasionally applied, quantity constraints based on car vintage are becoming increasingly popular. Our model provides a comprehensive analysis that explains this prevalence of quantity over price schemes. We also elucidate some other stylized facts observed in urban areas applying traffic restrictions, such as the implementation of hybrid price-and-quantity systems, the use of trial periods, the commitment to invest in public transit to enhance the acceptability of urban tolls, and the concentration of quantity restrictions in high-income cities.

1. Introduction

Private transportation in large cities generates significant negative externalities, both in terms of pollution and congestion. To mitigate these two negative externalities, economic theory suggests two alternative policy measures, depending on whether they are price- or quantity-based. Price-based measures, which mainly consist in charging urban tolls to enter/exit to/from the city center during peak hours are rarely implemented. In fact, tolls have only been successfully implemented in Singapore (1975), London (2003), Stockholm (2007), Milan (2008), Gothenburg (2013), and Palermo (2016).[1] Quantity-based measures take the form of driving restrictions that can either work through the intensive margin (number of miles driven) or through the extensive margin (type of car driven). As pointed out in Barahona et al. (2020), driving restrictions perform particularly poorly when designed to affect drivers' intensive margin as they treat all cars equally, regardless of how much they pollute.[2] Instead, vintage-specific restrictions concerning drivers' extensive margin that differentiate cars by their pollution rates are effective in moving the fleet composition

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* Corresponding author.
E-mail addresses: xfageda@ub.edu (X. Fageda), ricardo.flores@urv.cat (R. Flores-Fillol), bernd.theilen@urv.cat (B. Theilen).

[1] There are a few 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).

[2] The Economist (2016) suggests that driving restrictions may create perverse incentives for drivers to buy additional, higher-emitting vehicles. This is precisely the consequence of applying measures based on the intensive margin that are detached from car vintage. The best documented case is the license-plate ban program implemented in Mexico City in 1989 named *Hoy No Circula* (see Davis, 2008; Gallego et al., 2013).

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toward lower-emitting vehicles. Our study focuses on this type of vintage-specific restrictions, which are expanding throughout the European continent under the form of low emission zones (LEZ) that ban polluting vehicles (i.e., those not complying with emission standards) from city centers.[3] They have been implemented in 46 large cities from 12 European countries such as Berlin, Hamburg, Munich, Brussels, Milan, Rome, Paris, London or Madrid.

Before tackling the main challenges of our study, we look at some motivating evidence on the adoption of price and/or quantity restrictions in Europe. To do that, we perform a regression analysis that identifies the most relevant facts behind the implementation of LEZ in European cities over the period 2008–2020. Given that a similar analysis is unworkable for urban tolls due to the low number of cities implementing this policy,[4] we then review the experiences of the few cities having successfully applied them. Although our regression analysis finds partial evidence on the relevance of some city attributes (such as pollution, population density or the connectivity of public transportation networks), *urban income* is the regressor with the highest explanatory content, with particularly high marginal effects as compared to pollution and congestion. This result highlights the relevance of urban income in the adoption of LEZ, independently of the severity of either pollution or congestion. As for the successful European experiences in the application of urban tolls, we conclude that: (i) they are applied in cities where pollution and congestion problems are severe, (ii) trial periods are used to enhance their acceptability before their permanent implementation (Stockholm and Milan), (iii) some cities combine them with quantity restrictions (Milan and Palermo), and (iv) policy makers commit to invest in public transit to enhance their acceptability (London, Stockholm, Milan, Gothenburg, and Palermo). These empirical and descriptive results give rise to four *stylized facts* related to the acceptability of price- and quantity-based restrictions, which have not yet been addressed by the existing literature in a comprehensive way.

Our study constitutes a first attempt to understand the political-economy challenges underlying the adoption of price- and quantity-based measures to mitigate pollution and congestion in urban areas. We propose a unified framework explaining the four *stylized facts* from first principles. Our model assesses the effects of price and quantity restrictions on different population groups, which allows comparing their political support. We then adapt our baseline set-up to account for a number of relevant circumstances influencing the acceptability of both types of measures. First, we allow for individual uncertainty about commuters' willingness to pay. Second, we consider the existence of peak and off-peak periods, as congestion is usually restricted to specific time spans with intensive traffic (i.e., rush hours). This setting allows studying the combination of price measures limited to peak periods along with permanent quantity restrictions. Third, the analysis is extended to accommodate public transportation, which can be funded using toll revenues. Finally, we distinguish between urban residents (who live and work within the restricted area) and suburban residents (who commute to the urban core).

Our main findings can be summarized as follows. First, when a majority of citizens remain commuting after the implementation of traffic restrictions, there is a prevalence of quantity measures which are easier to implement and benefit high-income commuters. Therefore, they should be more easily accepted in high-income cities. Second, 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. Third, when congestion is restricted to peak periods and the amount of remaining peak drivers represents less than 50% of the population, a majority of citizens prefers a combination of price and quantity measures over an exclusive implementation of either tolls or quantity restrictions. Fourth, using toll revenues to subsidize public transit enhances the acceptability of tolls, although 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. And fifth, in a more sophisticated setting with heterogeneous population groups, LEZ are not always better accepted than urban tolls, but they are still preferred by those high-income remaining drivers who pay the toll.

Our study is related to the literature on price and quantity regulation of negative externalities caused by automobile use (see Parry et al., 2007 for a comprehensive survey). More precisely, it is connected to this literature in the following way. First, our focus is on *local* traffic pollution and congestion, as we compare (price versus quantity) regulatory policies on urban areas. Consequently, other environmental externalities such as global air pollution or macroeconomic instability related to fuel prices are not considered. In addition, given that price and quantity measures do not have a clear differential effect on traffic accidents, this negative externality is also disregarded.[5] Second, the price and quantity measures contemplated in our study are urban tolls and vintage-specific restrictions, respectively, as their adoption generally relies on local authorities. Therefore, other measures adopted at the national and/or state level are abstracted away from our analysis. These measures include, among others, price restrictions (such as fuel taxes or scrappage subsidies),[6] quantity restrictions (such as license-plate ban programs) or cap-and-trade schemes. Third, as in Weitzman (1974), our analysis departs from noticing that price and quantity instruments are equivalent in mitigating externalities, as both types of measures achieve the efficient outcome (first-best) under certainty in a fairly general model. While other studies highlight the nonequivalence between the two types of regulation when deviating from the seminal model assumptions (e.g., Weitzman, 1974; Cropper and Oates, 1992; Finkelshtain and Kislev, 1997; or Brueckner, 2009), our analysis maintains the equivalence between price and quantity instruments in terms of efficiency and focuses on the acceptability of both measures among different population groups.

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[3] Outside Europe, there are vintage-specific traffic restrictions, for instance, in Tokyo, Seoul or Santiago.

[4] Only two cities (Gothenburg in 2013 and Palermo in 2016) did implement this policy in the considered period. In addition, data for pollution and congestion are not available in the year before implementation for three out of the five European cities where tolls have been applied.

[5] Moreover, the impact of traffic restrictive measures on accidents is controversial, as lower traffic volumes reduce the amount of cars on the streets but increase their average speed. See Green et al. (2016) for an analysis of such effects in the case of London's congestion charge.

[6] Parry and Small (2005) study the optimality of gasoline taxes in the US and the UK.

Table 1
Large LEZ and non-LEZ cities in Europe.

LEZ cities (starting year)	Non-LEZ cities
Belgium: Antwerp (2017), Brussels (2019), Ghent (2020) *Czech Republic:* Prague (2016) *France:* Paris (2017) *Germany:* Berlin (2008), Bochum (2013), Bonn (2010), Bremen (2010), Cologne (2013), Dortmund (2013), Düsseldorf (2009), Duisburg (2013), Essen (2013), Frankfurt (2010), Hamburg (2018), Hanover (2010), Karlsruhe (2013), Leipzig (2011), Mannheim (2013), Münster (2010), Munich (2012), Stuttgart (2010), Wuppertal (2011) *Greece:* Athens (2018) *Italy:* Bologna (2016), Brescia (2019), 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:* Rotterdam (2016), Utrecht (2015) *Poland:* Kraków (2019) *Portugal:* Lisbon (2011) *Spain:* Barcelona (2020), Madrid (2018) *Sweden:* Stockholm (2020) *United Kingdom:* London (2019)	*Austria:* Vienna *Belgium:* Charleroi, Liège *Czech Republic:* Brno *Denmark:* Copenhagen *Finland:* Helsinki, Tampere *France:* Avignon, Bordeaux, Grenoble, Lille, Lyon, Marseille, Montpellier, Nantes, Nice, Rennes, Rouen, Saint-Etienne, Strasbourg, Toulon, Toulouse, Tours *Germany:* Bielefeld, Dresden, Nuremberg *Greece:* Thessaloniki *Hungary:* Budapest *Ireland:* Dublin *Italy:* Bari, Cagliari, Catania, Padua, Pescara, Taranto *The Netherlands:* Amsterdam, Eindhoven, The Hague *Poland:* Bydgoszcz, Gdańsk, Katowice, Lodz, Lublin, Poznan, Szczecin, Warsaw, Wroclaw *Portugal:* Porto *Romania:* Bucharest *Slovakia:* Bratislava *Spain:* Alicante, Bilbao, Córdoba, Las Palmas de Gran Canaria, Málaga, Murcia, Palma, Seville, Valencia, Valladolid, Zaragoza *Sweden:* Gothenburg *United Kingdom:* Belfast, Birmingham, Bournemouth, Brighton, Bristol, Cardiff, Coventry, Edinburgh, Glasgow, Hull, Leeds, Leicester, Liverpool, Manchester, Newcastle, Nottingham, Preston, Reading, Sheffield, Southampton, Stoke-on-Trent, Swansea

Notes: Cities with more than 300,000 inhabitants. LEZ for specific vehicles: Glasgow and Brighton (buses), Lyon and Grenoble (trucks, vans), Amsterdam, Copenhagen, Helsinki, and Gothenburg (trucks, buses), Vienna, Eindhoven, and The Hague (trucks). Emergency-LEZ in Lille, Marseille, Strasbourg, and Toulouse. Plans for LEZ for all vehicles in several cities in the UK and The Netherlands.

The rest of paper is organized as follows. Section 2 offers an overview of the existing experiences related to the application of price and quantity restrictions, including our empirical exercise on the factors behind the implementation of LEZ in European cities over the period 2008–2020. In Section 3, we present our baseline model to compare the acceptability of price and quantity restrictions. We then introduce individual uncertainty in Section 4. In Sections 5 and 6, we enrich our baseline set-up by allowing for peak and off-peak periods and the presence of public transit as an alternative transportation mode, respectively. Section 7 allows for the coexistence of urban and suburban residents. Finally, Section 8 offers a discussion on the generality of our analysis and Section 9 concludes by providing some policy recommendations. All proofs are provided in the Appendix.

2. Price versus quantity restrictions in European urban areas: Stylized facts

The EU has shown a clear determination in reducing negative externalities in urban areas, especially since the transposition of the directives 1999/30/EC and 2008/50/EC. This determination has been accompanied by the establishment of the 'Euro' regulatory standards for vehicles sold in EU member states. To accomplish this objective, European cities have implemented either urban tolls (price-based measures), LEZ (quantity-based measures) or a combination of both of them. In this section, we present a regression analysis identifying the most relevant facts behind the implementation of LEZ in European cities over the period 2008–2020, along with an overview of the existing European experiences related to the application of urban tolls (given that a regression analysis is unworkable for urban tolls due to the low number of cities implementing this policy). Then we use these empirical and descriptive results to formulate four *stylized facts* on the acceptability of price- and quantity-based restrictions, which are taken as the starting point in our analysis that is developed in Sections 3–7.

2.1. LEZ in European cities: Regression analysis

Although national regulatory frameworks may establish some rules (like the design of windscreen stickers for all vehicles depending on their emission level), the adoption decision and the implementation of LEZ (i.e., type of restricted vehicles, emission standards, boundaries, and fines) correspond to city councils. As compared to tolls, LEZ are much more popular and they are becoming widely applied in recent years. Focusing on large EU and UK cities (with a population exceeding 300,000 inhabitants), Table 1 indicates that 46 out of 130 cities have adopted comprehensive LEZ (affecting all types of vehicles) over the period 2008–2020.[7] LEZ adoption shows certain country-specific dynamics. While German and Italian large cities have generally applied LEZ, they are occasionally implemented in French, British or Spanish cities (being the only exceptions Paris, London, Madrid, and Barcelona) and in Eastern Europe metropolises (only in Prague and Krakow). LEZ are announced before their effective

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[7] In some cities, LEZ only apply to some specific vehicles like trucks, vans and/or buses. Instead, our focus is on general LEZ concerning all types of vehicles.

implementation. Although some cities do not fine violations during an initial period of few months, no trial periods have ever put in place.[8]

Although general wisdom would identify pollution as the main driver leading to the implementation of LEZ,[9] Fig. 1 underlines the potentially relevant effect of urban income. More precisely, the figure reveals that most LEZ cities are characterized by a per-capita income ($INCOME$) above the sample median, while there is a less clear pattern for pollution ($POLLUTION$) measured in terms of PM2.5.[10],[11]

To deepen our understanding on the causal effects of pollution and income in the adoption of LEZ, we carry out a regression analysis that includes additional control variables.[12] Specifically, we incorporate a congestion variable ($CONGESTION$) that measures the additional travel time a vehicle needs to undertake a trip in a certain city as compared to a free-flow situation.[13] We also account for the population density ($DENSITY$); a proxy for the quality of public transportation networks ($PUBLIC$); the number of cars per inhabitant ($CARS$); a measure for income inequality ($INEQUALITY$), computed as the P80/P20 ratio;[14] and a dummy that takes the value 1 when the mayor of the city is affiliated to a left-wing party ($IDEOLOGY$). All explanatory variables are lagged by one year. This specification has the advantage of focusing on the moment in which the decision is announced (typically about one year before their actual implementation).[15],[16]

The dependent variable is a dummy that measures the adoption of LEZ, taking value 1 in the implementation year. From this year onward, observations for LEZ cities are dropped from the sample.[17] To compensate for this loss of observations, cities that have adopted LEZ earlier are given a greater weight in the regression analysis.[18]

The regression results are shown in Table 2.[19] The coefficient of $INCOME$ is positive and statistically significant in all regressions, meaning that LEZ are more likely to be implemented in high-income cities. Although the coefficient of $POLLUTION$ is positive and statistically significant in Specifications I and II, it becomes insignificant when adding country fixed effects (Specification III).[20],[21] The coefficient of $CONGESTION$ is non significant in all specifications. Therefore, neither $POLLUTION$ nor $CONGESTION$ are determinant in the adoption of LEZ. This result is corroborated by observing that the marginal effects of $INCOME$ are notably higher than those of $CONGESTION$ and $POLLUTION$ (see Figure A1 in the Appendix). As for the rest of controls, none of them is significant throughout all the three specifications. Overall, these results reveal the preeminence of $INCOME$ in explaining the adoption of LEZ.

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[8] See CLARS (2020) for specific details on how LEZ have been implemented in European cities.

[9] Improving air quality is the main objective of the aforementioned directives 1999/30/EC and 2008/50/EC. In addition, it is important to acknowledge that 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).

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

[11] There are only three LEZ cities with an income clearly below the sample median (Palermo, Naples, and Lisbon). There are two additional LEZ cities with an income slightly below the sample median (Bochum, Turin). The rest of cities with an income below the median (60 cities) are non-LEZ cities (regardless their pollution records). Instead, there are 29 LEZ cities (out of 65 cities) with income higher than the median (and not particularly polluted). Even if we look at the extreme values, we still conclude that high income (and not high pollution) characterizes LEZ cities: (i) among the most polluted cities (higher than 15.3 $\mu g/m^3$ that identifies the most polluted decile), 10 out of 33 are LEZ cities, while (ii) among the highest per-capita income cities (higher than €61,500 that identifies the highest-income decile), 7 of 13 are LEZ cities.

[12] Details on the regression analysis are provided in Appendix A.

[13] Data from TomTom (2020).

[14] Ratio of the average income of the top 20% to the bottom 20% in the income distribution.

[15] In such a way, we account for the potential distortions that the adoption of LEZ could have on $POLLUTION$, $CONGESTION$ or $CARS$. Even though the precise lapse of time between announcement and implementation for each LEZ city could exceed one year, such lapse of time is expected to be short as the implementation of LEZ does not require high investments. In addition, the anticipation effect should be particularly important the year before the implementation of the measure.

[16] The approach in this paper focuses on short-run effects as they are dominant in electoral processes. Long run effects affecting decisions such as the choice of residential and workplace location (Redding and Rossi-Hansberg, 2017) go beyond the scope of our analysis.

[17] Our analysis focuses on the implementation year and uses congestion and pollution data from the previous year. Once LEZ have been implemented, the observations corresponding to LEZ cities are removed. Therefore, the post-implementation effect of LEZ on pollution and congestion does not affect our estimates and, consequently, no endogeneity bias is generated.

[18] In the framework of an unweighted regression analysis, the dependent variable has also been measured using two alternate specifications: (i) as a dummy giving the same weight to all LEZ cities regardless of the adoption moment; and (ii) as a dummy that takes value 1 from the implementation year onward without dropping any observation from the sample. These estimations, which yield qualitatively identical results, are available from the authors on request.

[19] The following equation is estimated to determine the influence of the explanatory variables on the adoption of LEZ by city i in country j at year t:

$$D_{ijt}^{LEZ} = \alpha + \beta_1 INCOME_{ijt-1} + \beta_2 POLLUTION_{ijt-1} + \beta_3 CONGESTION_{ijt-1} + \beta_4 DENSITY_{ijt-1}$$

$$+ \beta_5 PUBLIC_{ijt-1} + \beta_6 CARS_{ijt-1} + \beta_7 INEQUALITY_{jt-1} + \beta_8 IDEOLOGY_{ijt-1} + \delta_j + \lambda_t + \varepsilon_{ijt}.$$

[20] As for the existing literature on LEZ effectiveness, some studies for German cities suggest that LEZ can be effective in improving air quality, particularly for PM10 emissions (Malina and Scheffler, 2015; Morfeld et al., 2014; Wolff, 2014) yielding positive, albeit modest, health effects (Gehrsitz, 2017; Pestel and Wozny, 2021). Bernardo et al. (2021) reach a similar conclusion using a panel of large European urban areas. Some other studies analyze the effect of LEZ on individual cities (Cesaroni et al., 2012; Ellison et al., 2013; Panteliadis et al., 2014), obtaining results that vary depending on the analyzed city.

[21] Our dataset does not allow including city fixed effects. An estimation with city fixed effects would not converge to any value given that cities remaining in the same category (i.e., non-LEZ cities during the entire sample period) are automatically excluded from the regression. Therefore, our congestion and pollution variables may capture the effect of unobservable local policy measures like pedestrian zones, parking restrictions, biking infrastructure and so on. Instead, country fixed effects should control for national policy measures like fuel taxes.

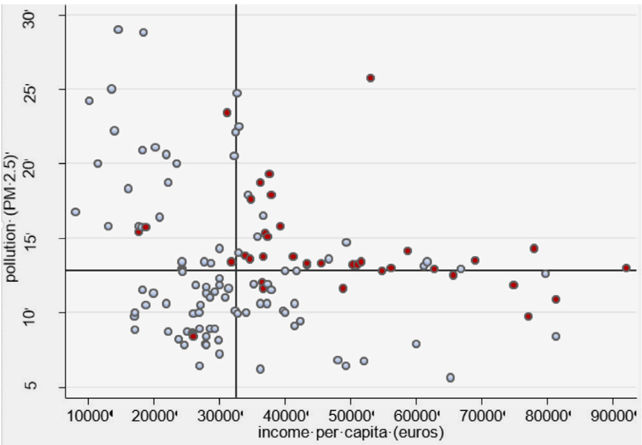

Fig. 1. Range scatter plot of $INCOME$ versus $POLLUTION$ in 2016 (red circles denote LEZ cities and gray circles non-LEZ cities).

Table 2
Estimation results of probit regressions.

	Dependent variable: D^{LEZ}		
	(I)	(II)	(III)
INCOME	0.030*** (0.006)	0.035*** (0.006)	0.028*** (0.007)
POLLUTION	0.061*** (0.018)	0.047** (0.020)	0.024 (0.041)
CONGESTION	0.001 (0.009)	0.004 (0.009)	0.022 (0.013)
DENSITY	–	−0.001 (0.001)	0.011** (0.004)
PUBLIC	–	0.056** (0.024)	0.006 (0.046)
CARS	–	0.039** (0.013)	−0.000 (0.025)
INEQUALITY	–	0.027 (0.086)	–
IDEOLOGY	–	0.369* (0.209)	0.111 (0.228)
Intercept	−3.400*** (0.626)	−5.918*** (0.825)	−5.884*** (1.162)
Country fixed effects	No	No	Yes
R^2	0.20	0.26	0.36
Observations	1148	1048	1075

Notes: Standard errors in parentheses (robust to heteroscedasticity and clustered at the city level). All regressions include year fixed effects. Statistical significance at 1% (***), 5% (**), 10% (*).

2.2. Urban tolls in European cities

While the literature on the effects of congestion pricing is extensive, few studies examine their acceptability. However, some works analyze the origin of urban tolls in the few cities where they have been implemented, along with the political strategies adopted by mayors to improve their popular support. The material that follows summarizes the challenges in terms of acceptability faced by the main European cities where urban tolls have been successfully applied.[22]

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[22] It should be also acknowledged that, additionally to the congestion charge, London (in 2019), Milan (in 2008), Stockholm (in 2020), and Palermo (in 2016) did also implement a low emission zone (see Table 1). LEZ are generally quantity-based measures banning vehicles not meeting the local emission standards to enter to (or exit from) a restricted area in the city center. However, the low emission zone in London is a special case, as it is the only city in our sample applying a low emission zone as a price-based measure. In addition to the congestion toll, vehicles that do not meet emission standards must pay an additional fee to enter to (or exit from) the restricted area.

London. Urban tolls were introduced in London in 2003 by Ken Livingstone, who won the 2000 London mayoral election with a left-wing platform including in its program an urban toll proposal. The reasons leading to this successful application were: (i) a severe pollution and congestion problem (ROCOL, 2000; Leape, 2006; Selmoune et al., 2020), (ii) a substantial investment in public transit just before the implementation, and (iii) the commitment to use most toll revenues to fund public transportation (Santos and Fraser, 2006; Albalate and Bel, 2009).

Stockholm. The congestion pricing initiative came about after the 2002 national election that led to the formation of a new government by the Social Democrats with the support of the Green Party. The new national government in cooperation with Stockholm's local government (also ruled by the Social Democrats) promoted a seven-months trial in 2006 accompanied by a referendum on its permanent implementation. The referendum resulted into an approval by 52% of the citizens and the urban toll was re-introduced permanently in 2007. The reasons leading to this successful application were: (i) the trial in 2006, which allowed the citizens to perceive directly the positive effects of the toll in terms of pollution and congestion mitigation (Eliasson, 2008; Hårsman and Quigley, 2010; Eliasson and Jonsson, 2011; Börjesson et al., 2012), and (ii) the introduction of new bus lines before the introduction of the toll (Kottenhoff and Brundell Freij, 2009).

Milan. In 2008, the right-wing mayor (Forza Italia) promoted a combined system named Ecopass including a low emission zone (banning the most polluting cars) and a toll also based on polluting emissions. In a public consultation on mid-2011, 79% of voters approved the continuation of Ecopass (Percoco, 2017) that was re-established on 2012 under the name of Area C as a 18-month pilot program. Area C was approved on a permanent basis in 2013. The Area C program is a congestion charge combined with a low emission zone, so that all vehicles meeting the emission standards are requested to pay a fixed daily charge in office hours. The move from a pollution to a congestion charge was explained by the fact that Ecopass was successful in reducing emissions but promoted the purchase of less polluting vehicles, perpetuating the congestion problem. The reasons behind the success in applying this policy were: (i) severe pollution and congestion problems, as Milan was one of the cities with the largest number of cars per inhabitant in the world along with adverse climate conditions resulting in very high pollution levels (Rotaris et al., 2010; Gibson and Carnovale, 2015),[23] (ii) the combination of this policy with a package of measures including investments in public transportation, (iii) the initial focus of Ecopass on pollution, which was perceived by Milan's citizens as the cause of serious health diseases, and (iv) the 18-month pilot program to let the citizens experience the effectiveness of the policy, thereby alleviating public objections.

Gothenburg. A time-differentiated congestion charge was introduced on 2013 by a coalition of parties leaded by the Social Democrats, despite the opposition of 57% of the citizens in a consultative referendum held in 2014. Although the pollution and congestion records in Gothenburg were not particularly severe and the majority of the citizens voted against the congestion charge,[24] the main purpose of the policy was in fact to raise funds because local co-funding was requested by the national government to carry out infrastructure investments (Börjesson and Kristoffersson, 2015; Andersson and Nässén, 2016).

Palermo. In 2016, the right-wing mayor (Forza Italia) launched a system replicating Milan's Area C. This policy was promoted in a context of an extremely high urban congestion, and its successful implementation was facilitated by the new tram network launched in December 2015 with four lines and 44 stations (although funding for this project was not directly related to toll revenues).[25]

Although the above experiences (except for the case of Gothenburg) seem to point at congestion as a relevant driver in the implementation of urban tolls, it is also true that: (i) these cities where also suffering from severe pollution, and (ii) there were many other cities even more congested that did not apply tolls (deciding instead to either apply LEZ or no policy at all). Overall, these results call for further analysis on the reasons explaining the decision to implement urban tolls.

2.3. Stylized facts

From the results of our regression analysis and the previous review of urban tolls in European cities, we can conclude that there is not a clear relationship between the implementation of either LEZ or tolls and the relative severity of either pollution or congestion. Instead, we can formulate the following *stylized facts* (*SF*) on the acceptability of price- and quantity-based restrictions, which are taken as the starting point in our analysis.

▶ *SF*-1. *There is a prevalence of quantity over price measures. Quantity measures are mostly applied in high-income cities (as pointed out by our regression analysis), while the relationship between urban income and the application of price schemes is unclear (due to the low number of cities implementing this policy).*

▶ *SF*-2. *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.*

▶ *SF*-3. *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.*

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[23] Using the data from our regression analysis corresponding to 2008, the mean congestion value is 24% while the value for Milan is 33%. As for pollution measured in annual PM2.5 emissions, the sample average is 16.1 μg/m^3 whereas Milan registered 30.1 μg/m^3, only exceeded by Krakow and Katowice. The substantial traffic reduction experienced in 2008 suggests an even higher gap before the implementation of Ecopass (AMMA, 2008).

[24] Using the data from our regression analysis corresponding to 2012, the registered congestion and PM2.5 emissions in Gothenburg were 21% and 5.1 μg/m^3, while the sample average were 23% and 14.82 μg/m^3, respectively.

[25] During 2015, the congestion in Palermo was 41% while our sample mean congestion was 25% (only Bucharest and Lodz registered higher levels). Instead, the PM2.5 emissions were 15.5 μg/m^3, a value slightly higher than the sample mean that was 14.1 μg/m^3.

▶ *SF*-4. *Although policy makers commit to invest in public transit to enhance the acceptability of urban tolls (London, Stockholm, Milan, Gothenburg, and Palermo), they clearly remain more unpopular than quantity measures.*

The existing literature falls short to explain these stylized facts, as the political economy behind the adoption of price and quantity restrictions has not yet been addressed in a comprehensive way. Nevertheless, some attempts trying to answer some of these stylized facts can be identified in the existing literature. We can use the findings from this literature to speculate on possible explanations for these stylized facts.

As for *SF*-1, several reasons can be put forward. First, even though both price and quantity measures are potentially equivalent instruments to mitigate pollution and congestion, there is a general perception (i) that pollution is a more severe externality,[26] and (ii) that quantity measures are more effective in curbing pollution.[27] 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 (as exposed in *SF*-3). 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.

Notwithstanding, these arguments are weak from first principles, as rational individuals should be aware of the equivalent effectiveness of price and quantity restrictions. In addition, price schemes are nowadays also cheap to implement using cameras for car plate recognition and have the advantage of raising revenues that can be used to fund investments in public transportation allowing to overcome their unpopularity. Finally, the reason behind the determinant role of urban income in the implementation of quantity-based measures remains unanswered.

Regarding *SF*-2, 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 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.[28]

However, the incidence of trial periods with the purpose of reducing the uncertainty of initial drivers with respect to quantity-based measures is still unknown. Consequently, further research is needed to ascertain whether uncertainty affects in a similar way price- and quantity-based measures.

As for *SF*-3, a combination of price and quantity measures can be deemed as a more popular policy as compared to a rise of existing tolls.[29] The resistance to any policy reform can give clues to the long-lasting discussions that delay the application of any measure in several cities.[30]

Still, the underlying reasons why some policy measures are more acceptable (such as the aforementioned combination of price and quantity restrictions) than others remains an open question.

Finally, concerning *SF*-4, 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.[31]

Yet, there is still a crucial unanswered question. Even when toll revenues are used to improve public transit, why do price restrictions remain difficult to implement (as there are only five cities in Europe that has effectively applied them) as compared to quantity restrictions?

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[26] Both externalities are associated with relevant economic costs (see EC, 2020). Quite naturally, when the traffic situation is *congested* or *over capacity* (which typically occurs during peak hours at main roads), the congestion costs are particularly high and probably exceed the overall pollution costs (even considering the most polluting vehicles). However, when the traffic situation is *near capacity* or *well below capacity*, (which typically occurs at secondary roads and during off-peak hours at main roads), the congestion costs are much lower than the pollution costs. Consequently, the claim suggesting that pollution is generally perceived as a more severe externality is sustained by its harmful health effects (and not by its economic cost). These harmful effects are made clear by the existence of critical thresholds for different types of pollutants provided by the World Health Organization (WHO). The pollution registered in most cities included in our sample (96 out of 126 cities) clearly exceeds these thresholds, which raises social concerns. By contrast, there is no equivalent indicator for congestion.

[27] Posada et al. (2015) suggest that quantity instruments can be very effective in curbing pollution.

[28] In the field of political economy, there is a relevant literature strand that explains resistance to policy reforms due to uncertainty (Fernandez and Rodrik, 1991), asymmetric information (Mitchell and Moro, 2006), imperfect monitoring of politicians (Dixit et al., 1997; Coate and Morris, 1999), or populist political decisions (Maskin and Tirole, 2004). See De Borger and Proost (2012) for a more detailed revision of this literature.

[29] 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.

[30] See footnote 28 for a literature review on the resistance to policy reform.

[31] See Small (1992), Goodwin (1994), Mayeres and Proost (2001), Parry and Bento (2001), Calthrop et al. (2010), or Kidokoro (2010). De Borger and Proost (2012) provide a more detailed revision of this literature.

In this paper, we propose a unified framework that can account for all these stylized facts from first principles. Our model assesses the effects of price and quantity restrictions on different population groups, which allows comparing their political support. Therefore, our study constitutes a first attempt to understand the political-economy challenges underlying the adoption of price- and quantity-based measures to mitigate congestion and pollution in urban areas. As it will be thoroughly exposed throughout the analysis, Section 3 provides the answer to *SF*- 1, Section 4 explains *SF*-2, Sections 5 and 7 elucidate *SF*- 3 and, finally, Section 6 gives an explanation to *SF*-4.

3. The baseline model

In this section, we present our basic set-up where drivers generate pollution and congestion while commuting. From the comparison between the equilibrium traffic and the social optimum, we propose two alternative policy measures to mitigate both externalities simultaneously: price restrictions versus vintage-specific quantity restrictions. For the sake of simplicity, we refer to these restrictions throughout the paper as urban tolls and LEZ, respectively (although there are other price-based measures such as taxes or scrappage subsidies and other vintage-specific quantity restrictions such as partial circulation bans).[32] Our model abstracts away from considerations on the relative implementation cost of urban tolls and LEZ, as both policies rely on similar technologies based on license plate recognition cameras. Therefore, there should not be significant differences in terms of implementation costs of the two measures.

3.1. Set-up, equilibrium, and social optimum

Our model departs from De Borger and Proost (2012), who study the effects of urban tolls on congestion. We extend their model by incorporating environmental externalities in the analysis and by considering LEZ as an alternative (quantity-based) policy.

Consider an urban area with N potential commuters. Commuting trips in this urban area cause two externalities: pollution and congestion. Vehicles are heterogeneous in terms of polluting emissions. Individuals (i.e., potential commuters) are indexed by i, which is uniformly distributed over the range $[0, N]$. We assume that consumers owning newer and less polluting cars are characterized by higher willingness to pay (WTP) for commuting trips.[33] A vehicle produces polluting emissions given by γi, with $\gamma > 0$.[34] Individual i's WTP is given by $a - bi$ (with $a > 0$ and $b > \underline{b} = \gamma(a-d)/d$).[35] Thus, the individual with highest WTP is $i = 0$ (with $WTP = a$), and the individual with lowest WTP is $i = N = a/b$ (with $WTP = 0$). Each individual i makes a decision on whether to commute or not based on the following utility function:

$$U_i = y_i + \max\{a - bi - \rho, 0\}, \tag{1}$$

where y_i denotes the amount of income that i spends on the consumption of other goods, and ρ is the users' generalized cost of a car trip (including both monetary and time costs). Accordingly, the aggregate inverse demand function is given by

$$\rho = a - bn, \tag{2}$$

where n denotes the share of potential users that effectively decide to drive.

The average cost of a commuting trip (AC) is assumed to be linear and given by

$$AC = d + cn, \tag{3}$$

where $d \in (0, a/2)$ captures travel time cost and $c > 0$ denotes congestion damage, so that cn represents average congestion costs.[36] Although pollution is relevant from an aggregated social perspective, it is neglected by commuters who behave atomistically. Therefore, the total social cost (SC) is given by

$$SC = dn + cn^2 + \gamma n^2/2, \tag{4}$$

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[32] De Borger and Proost (2013) argue that LEZ can be considered as a combined price–quantity measure as fines are imposed in case of non-compliance. Instead, we treat LEZ as pure quantity measures because recurrent violations of the regulations translate into progressively increasing fines and other (more severe) sanctions.

[33] Recent studies show that high-income households purchase newer and more fuel-efficient vehicles, even though they may be bigger (Davis and Knittel, 2019; Levinson, 2019). Beresteanu and Li (2011) and Kayser (2000) also provide evidence that higher-income consumers are more likely to buy more fuel-efficient cars. A negative relationship between vehicle age and income is also found in Miller et al. (2002) from a cross-county comparison within the US. In a similar vein, estimates of the income-demand elasticity for fuel consumption of new cars are generally negative, meaning that high-income consumers purchase more fuel-efficient vehicles (Bonilla and Foxon, 2009; Johansson and Schipper, 1997).

[34] This linear functional form is not essential to derive our results and could be replaced by any monotonically increasing function in i. It is assumed with the purpose of producing a more tractable analysis.

[35] Having a lower bound for b (i.e., the slope of the WTP) excludes the trivial solution where the whole population gains from restricting traffic through the implementation of either tolls or LEZ. This lower bound for b is derived in footnote 41.

[36] Note that having a constant d means that the value of time is assumed to be uniformly distributed across potential commuters. The upper bound $d < a/2$ simplifies the analysis under uncertainty in Section 4 (see proof of Proposition 2 in Appendix D.2).

where $\gamma n^2/2 = \gamma \int_0^n i\, di$ denotes the total pollution cost generated by commuting trips.[37] Pollution is equally distributed over the urban area, such that each individual bears $1/N$ of the total pollution cost.[38] Consequently, the marginal social cost (MSC) is given by

$$MSC = d + (2c + \gamma)\, n. \tag{5}$$

The market equilibrium is given by the condition $\rho = AC$, such that the number of drivers in equilibrium is given by

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

Instead, the social optimum is characterized by $\rho = MSC$, which yields

$$n^* = \frac{a-d}{b+2c+\gamma}, \tag{7}$$

meaning that, without any policy intervention, traffic is inefficiently high, i.e., $n^e > n^*$.

In the material that follows, we compare two optimal restrictive policies that aim at mitigating both externalities simultaneously (pollution and congestion): an urban toll (price-based restriction) and a low emission zone (vintage-specific quantity restriction). Even if the declared goal of urban tolls is to mitigate congestion whereas the declared goal of LEZ is to abate pollution, both policies have actual effects on the two externalities simultaneously. We consider that both policy tools encompass the double objective with the ultimate purpose of achieving efficiency. In such a way, they are comparable.

3.2. Urban tolls

A first policy intervention that allows aligning private and social incentives would be the implementation of an urban toll designed as a Pigouvian tax. The optimal toll t^* would be the value of the externality evaluated at the social optimum, i.e.,

$$t^* = MSC\left(n^*\right) - AC\left(n^*\right) = (c+\gamma)\, n^* = \frac{(c+\gamma)(a-d)}{b+2c+\gamma}, \tag{8}$$

which yields the following toll revenues:

$$t^* n^* = (c+\gamma)\left(n^*\right)^2 . \tag{9}$$

The proportion $\lambda \in [0,1]$ of these revenues is assumed to be equally distributed over the whole population of potential commuters,[39] while the remaining proportion $1-\lambda$ is sunk (i.e., the shadow cost of public funds explained by transaction costs and efficiency losses).[40] With the purpose of assessing the impact of this policy over the citizens, we classify the population N into three groups: *non-drivers*, *remaining drivers*, and *ex-drivers*.

Non-drivers are distributed over the interval $(n^e, N]$ and do not commute before the implementation of the toll. Therefore, they only obtain benefits from the application of the toll. More precisely, they receive toll revenues and the environmental gain derived from pollution abatement, which amounts to

$$\underbrace{\lambda \frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} > 0. \tag{10}$$

Remaining drivers are distributed over the interval $[0, n^*]$, meaning that they are characterized by a relatively high WTP and continue driving after the application of the toll. Besides the received toll revenues and environmental gains, they also benefit from time savings due to reduced congestion but they have to bear the cost of paying the toll, i.e.,

$$\underbrace{\lambda \frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} + \underbrace{c\left(n^e - n^*\right)}_{time\ gain} - \underbrace{t^*}_{toll} < 0, \tag{11}$$

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[37] The case with constant marginal pollution damage can be easily derived from our model by replacing $\gamma n^2/2$ by γn in (4). Moreover, given that pollution and congestion are strongly correlated, it could be argued that the actual pollution cost should depend both on the number of commuters (n) and on congestion (cn^2). In fact, the functional form of the total pollution cost $\gamma n^2/2$ can be interpreted in such a way as the composition of these two elements, i.e., $\gamma n^2/2 = \gamma' n^2/2 + \alpha c n^2/2$, where $\gamma = \gamma' + \alpha c$.

[38] More generally, individuals could be affected by total (local) pollution in a proportion $\eta \in [1/N, 1]$. Given that both pollution and population are equally distributed over the urban area, the case $\eta = 1/N$ assumed in our model emerges naturally. Solving the model without assuming a particular value for η would not have any qualitative effect in our results. More precisely, it can be checked that the equilibrium and socially-optimal values of the number of drivers, n^e and n^* (see expressions (6) and (7)) would remain unaffected, while the cutoff values $\tilde{n}$ and $\hat{n}$ would be affected exactly in the same proportion (see expressions (13) and (17)). Consequently, this generalization would only alter the size of the different groups of *ex-drivers* (see Fig. 2) while the global assessment on the acceptability of the different price and quantity restrictions under study would remain unchanged.

[39] Section 6 provides an extension of our baseline model that relaxes the assumption of an equal distribution of toll revenues. This extension contemplates the case in which toll revenues are earmarked to subsidize public transportation, which is a common practice accompanying price-based traffic restriction policies in many cities to enhance their acceptability, as pointed out in *SF*-4 (see Section 2).

[40] Strictly speaking, the toll derived as a Pigouvian tax in (8) is socially optimal only when $\lambda = 1$. However, when $\lambda < 1$, the specification of t^* as a Pigouvian tax is maintained for simplicity reasons and also acknowledging that our results do not depend on the size of λ. De Borger and Proost (2012) consider the case $\lambda = 1$ in their baseline model. Then they introduce the case $\lambda < 1$ and interpret it as *political uncertainty*, which refers to consumers' ex ante (i.e., before voting) perception on the efficiency of politicians.

as the cost of paying the toll exceeds the sum of the aforementioned gains, which can be verified by substituting (6)–(8) into (11).

Ex-drivers are distributed over the interval $(n^*, n^e]$ and stop driving as a consequence of the implementation of the toll. These individuals lose their value of the trip designated by their WTP (i.e., $a - bi$) but save the trip's AC and benefit from the distributed toll revenues and the environmental gain. Consequently, their net gains amount to

$$\underbrace{\lambda \frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} + \underbrace{(d + cn^e)}_{AC(n^e)} - \underbrace{(a - bi)}_{WTP} \gtreqless 0, \tag{12}$$

where the sign of (12) depends on the value of i. This expression is negative for $i = n^*$ as (12) equals (11) and positive for $i = n^e$ as (12) equals (10). The indifferent individual with respect to the application of the policy is

$$\tilde{n} = n^e - \frac{1}{b}\left(\underbrace{\lambda \frac{t^* n^*}{N}}_{toll\ revenue} + \underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental gain} \right), \tag{13}$$

where $n^* < \tilde{n} < n^e$ (details provided in Appendix B). Therefore, consumers in $(n^*, \tilde{n}]$ are harmed by the toll whereas consumers in $(\tilde{n}, n^e]$ are benefited. Quite naturally, the proportion of ex-drivers that are better off after the toll increases with the received revenues and environmental gains.

Given that non-drivers are better off after the toll, remaining drivers are worse off, and ex-drivers are divided as explained above, the following result emerges.

Lemma 1. *Comparing optimal urban tolls and the status quo (i.e., no policy), there is a majority in favor of urban tolls for* $\tilde{n} < N/2$. *The support is increasing with the share of redistributed toll revenues and the severity of pollution.*

3.3. LEZ

A second policy intervention based on LEZ consists in limiting the traffic volume by banning the most polluting cars. More precisely, optimal LEZ are vintage-specific measures restricting the circulation to vehicles polluting less than γn^*, which determines the stringency level of the policy. By achieving the efficient traffic level, LEZ deal simultaneously with pollution and congestion. As in the case of urban tolls, we can assess the effect of LEZ on the population by dividing the whole population N into *non-drivers*, *remaining drivers*, and *ex-drivers*.

Non-drivers are not affected by the restriction (independently of its stringency level) and receive the benefits of breathing a cleaner air due to the achieved pollution abatement, i.e.,

$$\underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} > 0. \tag{14}$$

Remaining drivers own the cleanest cars that are not affected by the application of the restriction. Therefore, they can continue driving on less congested roads (with the subsequent time saving) in a less polluted atmosphere, i.e.,

$$\underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} + \underbrace{c\left(n^e - n^*\right)}_{time\ gain} > 0. \tag{15}$$

Ex-drivers lose their value of the trip but save the trip's AC and receive the environmental gains, i.e.,

$$\underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain} + \underbrace{(d + cn^e)}_{AC(n^e)} - \underbrace{(a - bi)}_{WTP} \gtreqless 0, \tag{16}$$

which is positive for $i = n^e$ as (12) equals (14) and negative for $i = n^*$.[41] The indifferent citizen with respect to the application of the policy is now

$$\hat{n} = n^e - \frac{1}{b} \underbrace{\gamma \frac{(n^e)^2 - (n^*)^2}{2N}}_{environmental\ gain}, \tag{17}$$

where $n^* < \hat{n} < n^e$ (details provided in Appendix B), with consumers in $(n^*, \hat{n}]$ being harmed and consumers in $(\hat{n}, n^e]$ being benefited. As with the urban toll, non-drivers are better off and ex-drivers are divided. Remaining drivers are also benefited by the application of this policy measure, so that the following result arises.

Lemma 2. *Comparing optimal* LEZ *and the status quo (i.e., no policy), there is a majority in favor of* LEZ *for* $\hat{n} - n^* < N/2$.

---

[41] When $i = n^*$, (16) becomes $-\frac{1}{2} b (c + \gamma)(a - d) \frac{2ab^2 + 4ac^2 + bd\gamma + 2cd\gamma + bc(6a - d) + (c + \gamma)d(b - \underline{b})}{a(b+c)^2 (b + 2c + \gamma)^2}$, which is negative as $b > \underline{b}$ and $a > d$.

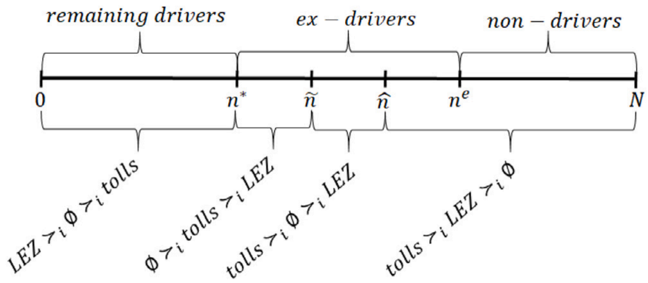

Fig. 2. Policy comparison.

3.4. Policy comparison

In this subsection, we compare the effect of the three alternatives (no policy, tolls, and LEZ) on each population group: non-drivers, remaining drivers, and ex-drivers. Non-drivers receive environmental gains both under tolls and LEZ and, in addition, they receive some extra revenues under tolls. Therefore, $tolls \succ_i LEZ \succ_i \varnothing$ for $i \in (n^e, N]$ where $\varnothing$ stands for the status quo (i.e., no policy). Comparing with the status quo, remaining drivers benefit from the congestion and environmental gains implied by both tolls and LEZ. However, they are worse off under tolls as the cost of paying the toll exceeds the sum of the aforementioned gains (see (11)) and better off under LEZ (see (15)) as they obtain these gains at no cost. Consequently, $LEZ \succ_i \varnothing \succ_i tolls$ for $i \in [0, n^*]$. Finally, ex-drivers obtain equal benefits from both policies except for the extra revenues received under tolls, so that they prefer tolls to LEZ.

Introducing the status quo as a voting alternative makes the comparison somewhat more complicated, as we need to distinguish among three different types of ex-drivers depending on their WTP (high, medium, and low). More precisely, it is easy to check from (12) and (16) along with the ordering $n^* < \widetilde{n} < \widehat{n} < n^e$ (see Appendix B) that $\varnothing \succ_i tolls \succ_i LEZ$ for high WTP ex-drivers $i \in (n^*, \widetilde{n}]$, $tolls \succ_i \varnothing \succ_i LEZ$ for medium WTP ex-drivers $i \in (\widetilde{n}, \widehat{n}]$, and $tolls \succ_i LEZ \succ_i \varnothing$ for low WTP ex-drivers $i \in (\widehat{n}, n^e]$. This analysis is illustrated in Fig. 2 and summarized in the proposition below.

Proposition 1. *Comparing the three alternatives, then* $LEZ \succ_i \varnothing \succ_i tolls$ *for* $i \in [0, n^*]$, $\varnothing \succ_i tolls \succ_i LEZ$ *for* $i \in (n^*, \widetilde{n}]$, $tolls \succ_i \varnothing \succ_i LEZ$ *for* $i \in (\widetilde{n}, \widehat{n}]$, *and* $tolls \succ_i LEZ \succ_i \varnothing$ *for* $i \in (\widehat{n}, N]$.

Under majority voting, a pairwise comparison between $\varnothing$ and $tolls$ and between $\varnothing$ and LEZ yields the following result.

Corollary 1. *Departing from the status quo (i.e., no policy),* LEZ *are easier to implement than tolls as* $\widetilde{n} > \widehat{n} - n^*$ *is always observed.*

Proof. Provided in Appendix D.

This corollary follows from observing that the number of remaining drivers $i \in [0, n^*]$ is larger than the number of medium WTP ex-drivers $i \in (\widetilde{n}, \widehat{n}]$ as $\widetilde{n} > \widehat{n} - n^*$, given that consumers in $i \in (n^*, \widetilde{n}]$ prefer the status quo to either tolls or LEZ and that consumers in $i \in (\widehat{n}, N]$ prefer either tolls or LEZ to the status quo. While remaining drivers are in favor of the adoption of LEZ and against tolls, the opposite is observed for medium WTP ex-drivers.

Sometimes, when the effects of the externalities are severe, the application of a policy measure is obliged and the status quo is not an option. In such a case, the following corollary can be formulated.

Corollary 2. *Comparing optimal urban tolls and* LEZ*, there is a majority in favor of* LEZ *for* $n^* > N/2$*. The support for* LEZ *decreases with congestion and environmental damages as* $\partial n^*/\partial c < 0$ *and* $\partial n^*/\partial \gamma < 0$.

The above corollary is easy to understand because only remaining drivers (i.e., individuals characterized by the highest WTP) prefer LEZ to tolls. As the number of remaining drivers decreases in the presence of more severe pollution and congestion, LEZ would consequently receive less support than tolls.[42]

Therefore, the preference of LEZ over tolls requires a majority of remaining drivers (i.e., exceeding 50% of the total population) to be observed after the implementation of either tolls or LEZ. This condition is more likely to be fulfilled in high-income cities, which are characterized by a larger proportion of remaining drivers who own the less polluting cars that are not affected by LEZ. Additionally, this condition seems to hold in most urban areas as actual tolls and LEZ usually have a very limited effect in terms of traffic reduction, thereby providing a rationale on the prevalence of LEZ over urban tolls. These two findings provide an explanation to *SF*-1 (see Section 2).

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[42] As remaining drivers are the ones characterized by the highest WTP and own the cleanest cars, LEZ are expected to be more regressive than urban tolls.

4. Uncertainty

In this section, we study the effect of individual uncertainty.[43] Initial drivers are uncertain about their situation after the implementation of a policy (either tolls or LEZ). More precisely, they do not know exactly whether they will remain commuting (becoming remaining drivers) or stop driving (becoming ex-drivers) because they cannot perfectly foresee whether they will be interested in paying the toll or whether they will be affected by LEZ (which depends on their stringency level).

Following De Borger and Proost (2012) and Fernandez and Rodrik (1991), we model this individual uncertainty by assuming that initial drivers within the range $(0, n^e]$ are ex ante unsure about their WTP.[44],[45] The timing of events is as follows. First (before the implementation of any restriction), initial drivers know the actual travel flow (n^e) and that their WTP ($WTP = a - bi$) follows a uniform distribution over the interval $[0, n^e]$. Second, policy makers announce the policy measure to be applied (either tolls or LEZ) together with the target in terms of pollution abatement and congestion mitigation to be achieved (i.e., the socially optimal traffic level n^*).[46] Finally, initial drivers form their expectations taking into account their expected gains/losses about becoming either remaining drivers or ex-drivers and vote in favor or against the proposed policy measure. Consequently, their voting decision is based on their expected gain of becoming either remaining or ex-drivers. In this framework, the expected gain for an initial driver (ID) is computed using a Bayesian updating process.

Under urban tolls, the expected gain for an ID given that he/she would become a remaining driver (RD) is

$$\Delta Eu^{toll}(ID|RD) = \underbrace{EWTP^{toll}(ID|RD)}_{a-bn^*/2} - \underbrace{EWTP^{\varnothing}(ID|RD)}_{a-bn^*/2} + \Delta E\pi^{toll}(ID|RD), \tag{18}$$

where $\Delta E\pi^{toll}(ID|RD)$ denotes the additional net benefits for a RD after the application of the toll (i.e., *toll revenue* + *environmental gain* + *time gain* − *toll*). On the other hand, the expected gain for an ID given that he/she would become an ex-driver (ED) is

$$\Delta Eu^{toll}(ID|ED) = \underbrace{EWTP^{toll}(ID|ED)}_{0} - \underbrace{EWTP^{\varnothing}(ID|ED)}_{a-b(n^*+n^e)/2} + \Delta E\pi^{toll}(ID|ED), \tag{19}$$

where $\Delta E\pi^{toll}(ID|ED)$ denotes the additional net benefits for an ED after the application of the toll (i.e, *toll revenue* + *environmental gain* + *average cost savings*).

Given that the probabilities of becoming either a RD or an ED are given by $prob(RD) = n^*/n^e$ and $prob(ED) = (n^e - n^*)/n^e$, the expected gains for an ID related to the implementation of urban tolls are

$$\begin{aligned} \Delta Eu^{toll}(ID) = {} & \underbrace{\frac{n^*}{n^e}}_{prob(RD)} \times \underbrace{\left\{ \lambda \frac{t^* n^*}{N} + \gamma \frac{(n^e)^2 - (n^*)^2}{2N} + c\left(n^e - n^*\right) - t^* \right\}}_{\Delta Eu^{toll}(ID|RD)} \\ & + \underbrace{\frac{n^e - n^*}{n^e}}_{prob(ED)} \times \underbrace{\left\{ \lambda \frac{t^* n^*}{N} + \gamma \frac{(n^e)^2 - (n^*)^2}{2N} + (d + cn^e) - \left[a - b\left(\frac{n^* + n^e}{2}\right)\right] \right\}}_{\Delta Eu^{toll}(ID|ED)}. \end{aligned} \tag{20}$$

Under LEZ, following a similar reasoning, initial drivers form the following expectation:

$$\begin{aligned} \Delta Eu^{LEZ}(ID) = {} & \underbrace{\frac{n^*}{n^e}}_{prob(RD)} \times \underbrace{\left\{ \gamma \frac{(n^e)^2 - (n^*)^2}{2N} + c\left(n^e - n^*\right) \right\}}_{\Delta Eu^{LEZ}(ID|RD)} \\ & + \underbrace{\frac{n^e - n^*}{n^e}}_{prob(ED)} \times \underbrace{\left\{ \gamma \frac{(n^e)^2 - (n^*)^2}{2N} + (d + cn^e) - \left[a - b\left(\frac{n^* + n^e}{2}\right)\right] \right\}}_{\Delta Eu^{LEZ}(ID|ED)}. \end{aligned} \tag{21}$$

It can be shown that (20) is negative ($\Delta Eu^{toll}(ID) < 0$) whereas (21) is positive ($\Delta Eu^{LEZ}(ID) > 0$), which gives rise to the following result.

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[43] This individual uncertainty should be understood as preference (or voting) uncertainty, which is different from policy uncertainty about aggregate outcomes (Weitzman, 1974).

[44] Note that there is a one-to-one relationship between WTP and car emission levels.

[45] It could be argued that initial drivers with very-high (very-low) WTP do not face this kind of uncertainty, as they know for sure that they will continue (stop) driving. However, as long as there is a group of initial drivers with medium WTP suffering from individual uncertainty, the results of our analysis would remain qualitatively unchanged. An extension in this vein is sketched out in De Borger and Proost (2012).

[46] It could be argued that individual uncertainty affects urban tolls and LEZ asymmetrically. However, the relevance of our results has to do with the different effect of individual uncertainty in the two considered cases, independently of their relative size. Assuming asymmetric degrees of uncertainty under urban tolls and LEZ would leave our results qualitatively unchanged.

Proposition 2. *When initial drivers are uncertain about their WTP, they underestimate the positive effects of urban tolls (meaning that a larger fraction would oppose) and overestimate the positive effects of LEZ (meaning that a larger fraction would support them).*

Proof. Provided in Appendix D.

The intuition behind this result is as follows. Under certainty, initial drivers end up either better off or worse off after the implementation of urban tolls depending on their WTP. More precisely, as it has been reported in Section 3.2 and Fig. 2, those characterized by a high WTP (remaining and ex-drivers with a high WTP) end up worse off and those characterized by a low WTP (ex-drivers with a low WTP) end up better off. Under uncertainty, initial drivers are unaware about their WTP and expect to be worse off after the implementation of urban tolls (i.e., $\Delta Eu^{toll}(ID) < 0$) because, within the group of initial drivers, tolls are only beneficial for ex-drivers with a low WTP. Therefore, the negative effect of tolls on remaining and ex-drivers with a high WTP outweights the positive effect on ex-drivers with a low WTP.

Consequently, the main difference between the analysis under certainty and under uncertainty is that initial drivers characterized by a low WTP would vote in favor of the implementation of urban tolls under certainty whereas they would vote against under uncertainty. Thus, under uncertainty, some initial drivers underestimate the positive effects of urban tolls as stated in Proposition 2 above.

Similarly, the analysis of LEZ under certainty also reveals that initial drivers end up either better off or worse off after the implementation of the measure depending on their WTP (see Section 3.3 along with Fig. 2). More precisely, those characterized by either a high WTP (remaining drivers) or a low WTP (ex-drivers with a low WTP) end up better off and those characterized by an intermediate WTP (ex-drivers with a high WTP) end up worse off. Instead, under uncertainty, initial drivers are unaware about their WTP and expect to be better off after the implementation of LEZ (i.e., $\Delta Eu^{LEZ}(ID) > 0$) because, within the group of initial drivers, LEZ are only harmful for ex-drivers with a high WTP. Therefore, the positive effect of LEZ on remaining and ex-drivers with a low WTP outweights the negative effect on ex-drivers with a high WTP.

Consequently, the main difference between the analysis under certainty and under uncertainty is that initial drivers characterized by an intermediate WTP would vote against the implementation of LEZ under certainty whereas they would vote in favor under uncertainty. Thus, under uncertainty, some initial drivers overestimate the positive effects of LEZ as stated in Proposition 2 above.

This is an important result as it provides a theoretical background explaining the underlying reasons of the ex ante resistance to tolls as opposed to LEZ. Commuters are uncertain regarding the effect of both policies, being overoptimistic about the consequences of LEZ and overpessimistic about those of tolls. As a consequence, a successful introduction of urban tolls benefits from trial periods that help dispelling this individual uncertainty (as we can observe from the experiences in Stockholm and Milan). By contrast, trials would undermine the acceptability of LEZ, a finding that is fully consistent with the absence of trial periods preceding the permanent implementation of LEZ. These results explain *SF*-2 (see Section 2).

5. Peak and off-peak periods

Up to now, we have considered that pollution and congestion are always present and affect every commuter at any moment. Instead, the current application of urban tolls in cities is typically limited to peak periods (i.e., morning and afternoon rush hours). In this section, we account for this circumstance by allowing for peak (congested) and off-peak (uncongested) periods, which requires the design of targeted measures.

5.1. Set-up, equilibrium, and social optimum

In our baseline model, the N potential commuters decide whether to drive or not. Instead, in this section individuals have three alternatives. They can commute during a peak period (time span with intensive traffic and road congestion), during an off-peak period (uncongested traffic) or not to drive at all.[47] Commuting in the peak period generates higher utility than in the off-peak period. Accordingly, commuter i's $WTPs$ are given by $WTP_p = a_p - b_p i$ and $WTP_o = a_o - b_o i$, where subindices p and o denote peak and off-peak, respectively (with $a_p - a_o > a_o - d > 0$, $b_o > 0$ and $b_p \in (\underline{b}_p, \overline{b}_p)$, where $\underline{b}_p = \left(b_o + \gamma\right)\frac{a_p - d}{a_o - d} - (\gamma + c)$ and $\overline{b}_p = b_o - 2c + \frac{(c+\gamma)(a_p - a_o)(b_o+\gamma)}{(a_o - d)\gamma}$).[48] Consequently, denoting n_p, n_o, and n_t the number of peak, off-peak, and total drivers, respectively, the aggregate inverse demand functions for peak and off-peak drivers are given by $\rho_p = a_p - b_p n_p$ and $\rho_o = a_o - b_o n_o$. Thus, the condition determining the number of potential commuters $N = a_o/b_o$ emerges naturally. The average cost of a commuting trip is $AC_p = d + cn_p$ during the peak period while it amounts to $AC_o = d$ during the off-peak period as there is no congestion. The discussion that follows derives the market equilibrium and social-optimum traffic levels, both during peak and off-peak periods. The complete analysis is summarized in Fig. 3 and details on the computations carried out in this subsection are provided in Appendix C.

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[47] The cost to shift from peak to off-peak periods may be heterogeneous across commuters, depending on their individual commitments or obligations. Our model aims at capturing the adaptive behavior of some peak commuters and, therefore, it abstracts away from such heterogeneous switching costs, which would not change our results qualitatively.

[48] Having a lower bound for b_p ensures that the equilibrium and the socially optimal off-peak traffic is strictly positive (see Appendix C). Having an upper bound for b_p guarantees that, in equilibrium, peak-period tolls are higher than off-peak-period tolls (see footnote 50).

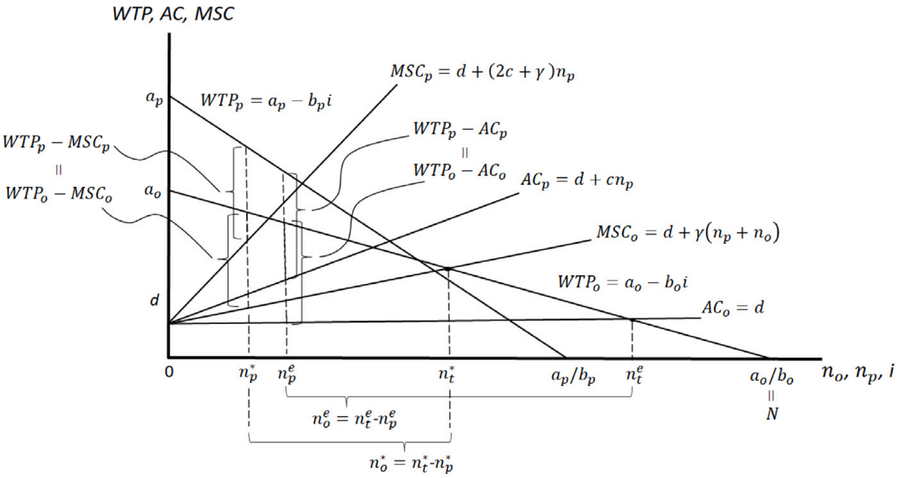

Fig. 3. Peak and off-peak periods.

Individuals commute during the peak period under two conditions: (i) they should obtain a positive net utility (so that driving is better than staying at home), and (ii) this utility has to be higher than the one they would obtain if commuting during the off-peak period, i.e.,

$$\begin{aligned} &WTP_p - AC_p \geqslant 0 \ \text{ and} \\ &WTP_p - AC_p \geqslant WTP_o - AC_o \ \text{ for } i \in [0, n_p]. \end{aligned} \tag{22}$$

In equilibrium, the first constraint in (22) is nonbinding and the second one determines the equilibrium number of peak drivers, which is given by

$$n_p^e = \frac{a_p - a_o}{b_p - b_o + c}. \tag{23}$$

Similarly, individuals decide to commute during the off-peak period when this alternative is simultaneously better than staying at home and than driving during the peak period, i.e.,

$$\begin{aligned} &WTP_o - AC_o \geqslant 0 \ \text{ and} \\ &WTP_o - AC_o \geqslant WTP_p - AC_p \ \text{ for } i \in (n_p, n_t]. \end{aligned} \tag{24}$$

As observed in Fig. 3, the second expression is nonbinding for $i > n_p^e$ and, consequently, the first one determines the total number of commuters (n_t^e), which is given by

$$n_t^e = \frac{a_o - d}{b_o}, \tag{25}$$

so that the equilibrium off-peak traffic is given by

$$n_o^e = n_t^e - n_p^e = \frac{\gamma\left(a_p - a_o\right) + \left(a_o - d\right)\left(b_p - \underline{b}\right)}{b_o\left(c - b_o + b_p\right)} > 0. \tag{26}$$

While pollution in urban areas is present both in peak and off-peak periods, congestion is limited to peak periods. Therefore, the MSC depends on whether the period is either peak or off-peak, being $MSC_p = d + (2c + \gamma)\, n_p$ and $MSC_o = d + \gamma n_t$, respectively.[49] Therefore, following a similar reasoning as before, the socially-optimal traffic during the peak period is given by the conditions

$$\begin{aligned} &WTP_p - MSC_p \geqslant 0 \ \text{ and} \\ &WTP_p - MSC_p \geqslant WTP_o - MSC_o \ \text{ for } i \in [0, n_p], \end{aligned} \tag{27}$$

---

[49] The underlying social cost functions that give rise to MSC_p and MSC_o are $SC_p(n_p) = dn_p + cn_p^2 + \frac{\gamma}{2}n_p^2$ and $SC_o(n_o) = dn_o + \frac{\gamma}{2}\left(n_p + n_o\right)^2 - \frac{\gamma}{2}n_p^2$. On the one hand, it can be observed that $SC_p(n_p)$ incorporates the congestion externality whereas $SC_o(n_o)$ does not include it. On the other hand, both expressions take into account the pollution externality that depends on the total number of vehicles. Taking into account that commuters are ordered in terms of WTP, the expression $SC_p(n_p)$ only incorporates peak drivers while $SC_o(n_o)$ departs from the existing social cost in $SC_p(n_p)$ and adds up the one generated by off-peak drivers. This modeling choice allows recovering the social cost from the baseline model in (4), as $SC = SC_p(n_p) + SC_o(n_o)$. The rationale behind this specification is that pollutants do not vanish when switching from the peak to the off-peak period and vice versa, which seems a rather realistic consideration.

where the first condition is nonbinding. Hence, the second constraint in (27) is binding and determines the socially-optimal number of peak drivers, which is given by

$$n_p^* = \frac{a_p - a_o}{b_p - b_o + 2c}. \tag{28}$$

Finally, the socially-optimal number of off-peak drivers is therefore determined by

$$\begin{aligned} &WTP_o - MSC_o \geqslant 0 \ \text{ and} \\ &WTP_o - MSC_o \geqslant WTP_p - MSC_p \ \text{ for } i \in (n_p, n_t], \end{aligned} \tag{29}$$

where the second constraint is nonbinding while the first one yields the socially-optimal number of commuters

$$n_t^* = \frac{a_o - d}{b_o + \gamma}. \tag{30}$$

The socially-optimal off-peak traffic is given by

$$n_o^* = n_t^* - n_p^* = \frac{\left(a_o - d\right)\left(b_p - \underline{b} + c\right)}{\left(\gamma + b_o\right)\left(2c - b_o + b_p\right)} > 0. \tag{31}$$

Regarding the equilibrium and socially-optimal number of peak and off-peak drivers, the following order can be established: $0 < n_p^* < n_p^e < n_t^* < n_t^e < N$.

5.2. Urban tolls

Aligning private and social incentives using price-based measures requires applying discriminatory tolls for peak and off-peak periods, given that the externality and the social optimum differ during each type of period. Proceeding as before, these optimal urban tolls are

$$t_p^* = MSC_p - AC_p = (c + \gamma)\, n_p^* = \frac{(c + \gamma)\left(a_p - a_o\right)}{b_p - b_o + 2c} \ \text{ and} \tag{32}$$

$$t_o^* = MSC_o - AC_o = \gamma n_t^* = \gamma \frac{a_o - d}{b_o + \gamma}, \tag{33}$$

where $t_p^* > t_o^*$, i.e., tolls are higher during peak periods.[50] The revenues obtained from these tolls (T) are

$$T = t_p^* n_p^* + t_o^* n_o^* = (c + \gamma)(n_p^*)^2 + \gamma n_t^* (n_t^* - n_p^*). \tag{34}$$

To assess the impact of this policy over the citizens, we need to classify the population N into five groups: *non-drivers*, *ex-off-peak drivers* (initial off-peak drivers that become non-drivers), *remaining off-peak drivers*, *ex-peak drivers* (initial peak drivers that become off-peak drivers), and *remaining peak drivers*. Taking into account the equilibrium and social-optimum values computed above, it is straightforward to assign these population groups to the following intervals: *non-drivers* are located in $(n_t^e, N]$, *ex-off-peak drivers* in $(n_t^*, n_t^e]$, *remaining off-peak drivers* in $(n_p^e, n_t^*]$, *ex-peak drivers* in $(n_p^*, n_p^e]$, and *remaining peak drivers* in $\left[0, n_p^*\right]$. Table 3 summarizes in a synthetic way the effect of the considered policies over each group.

It is important to realize that the environmental gains derived from the implementation of tolls (i.e., $\gamma \frac{\left(n_t^e\right)^2 - \left(n_t^*\right)^2}{2N}$) come exclusively from the ex-off-peak drivers that become non-drivers and stay at home, as ex-peak drivers become off-peak drivers and generate the same level of pollution before and after tolls. It should also be noted that ex-peak drivers, besides paying the off-peak toll and receiving toll revenues and environmental gains, lose the difference between their value of the trip during peak and off-peak periods, i.e., $WTP_p - WTP_o = a_p - a_o - \left(b_p - b_o\right) i$. By contrast, they save the difference between the cost per trip during peak and off-peak periods, i.e., $AC_p(n_p^e) - AC_o = c n_p^e$.

5.3. LEZ

We now focus on the effect of LEZ, as an alternative quantity-based measure restricting traffic. Proceeding in a similar way as with urban tolls, we now design discriminatory optimal LEZ for peak and off-peak periods. The social optimum is attained by implementing two LEZ: a more stringent one during the peak period and a less stringent one during the off-peak period. In such a way, only vehicles polluting less than γn_p^* are allowed to circulate during peak periods, while the cars permitted during off-peak periods need to comply with the emission threshold γn_t^*. We can establish the same population groups as before, with Table 3 condensing the effect of LEZ on each of them. It is worthwhile to mention that remaining off-peak drivers do not obtain any time gains under LEZ given that the off-peak period is uncongested. As for the analysis of ex-peak drivers with respect to the difference between their value of the trip and the AC during peak and off-peak periods, we obtain the same expressions as under urban tolls.

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[50] Note that $t_p^* - t_o^* = \frac{\gamma\left(a_o - d\right)\left(\bar{b}_p - b_p\right)}{(\gamma + b_o)(b_p - b_o + 2c)} > 0$.

Table 3
tolls, *LEZ*, and *comb* during peak and off-peak periods.

Group	*tolls*	*LEZ*	*comb*	Ranking
remaining peak drivers $[0, n_p^*]$	$\underbrace{\lambda \frac{T}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.gain} \underbrace{+c(n_p^e-n_p^*)}_{time\ gain} \underbrace{-(c+\gamma)n_p^*}_{peak\ toll}$	$\underbrace{\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} \underbrace{+c(n_p^e-n_p^*)}_{time\ gain}$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} \underbrace{+c(n_p^e-n_p^*)}_{time\ gain} \underbrace{-(c+\gamma)n_p^*}_{peak\ toll}$	$LEZ \succ_i tolls \succ_i comb$
ex − peak drivers $(n_p^*, n_p^e]$	$\underbrace{\lambda \frac{T}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{cn_p^e}_{AC_p-AC_o} \underbrace{-[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o} - \underbrace{\gamma n_t^*}_{off\ toll}$	$\underbrace{\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{cn_p^e}_{AC_p-AC_o} \underbrace{-[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o}$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{cn_p^e}_{AC_p-AC_o} \underbrace{-[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o}$	$comb \succ_i LEZ \succ_i tolls$ if $\gamma < \tilde{\gamma}$ $comb \succ_i tolls \succ_i LEZ$ if $\gamma > \tilde{\gamma}$
remaining off-peak drivers $(n_p^e, n_t^*]$	$\underbrace{\lambda \frac{T}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} - \underbrace{\gamma n_t^*}_{off\ toll}$	$\underbrace{\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain}$	$comb \succ_i LEZ \succ_i tolls$ if $\gamma < \tilde{\gamma}$ $comb \succ_i tolls \succ_i LEZ$ if $\gamma > \tilde{\gamma}$
ex-off-peak drivers $(n_t^*, n_t^e]$	$\underbrace{\lambda \frac{T}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{d}_{AC_o} \underbrace{-(a_o-b_o i)}_{WTP_o}$	$\underbrace{\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{d}_{AC_o} \underbrace{-(a_o-b_o i)}_{WTP_o}$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain} + \underbrace{d}_{AC_o} \underbrace{-(a_o-b_o i)}_{WTP_o}$	$tolls \succ_i comb \succ_i LEZ$
non−drivers $(n_t^e, N]$	$\underbrace{\lambda \frac{T}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} \underbrace{+\gamma \frac{(n_t^e)^2-(n_t^*)^2}{2N}}_{environ.\ gain}$	$tolls \succ_i comb \succ_i LEZ$

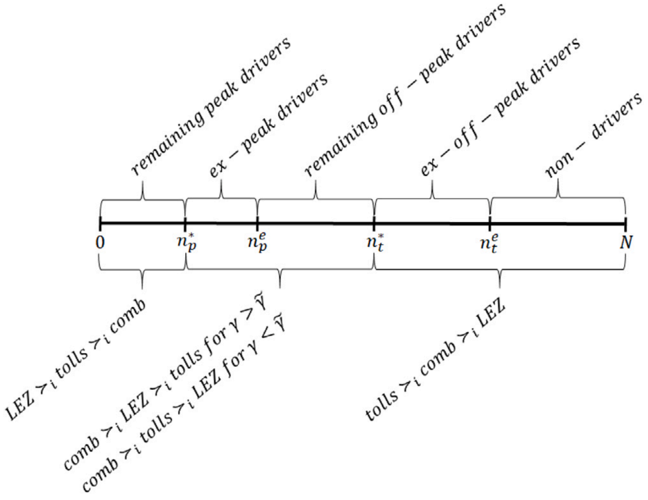

Fig. 4. Policy comparison under peak and off-peak periods.

5.4. Combination of urban tolls and LEZ

An interesting third alternative is the implementation of a combination of urban tolls and LEZ, denoted by $comb$. This policy permanently bans any car producing emissions higher than the threshold γn_t^* (as with the less stringent low emission zone applied during off-peak periods in the previous scenario) while charging a toll t_p^* limited to peak periods.[51] Therefore, the low emission zone is now milder as it only affects off-peak commuters who own the most polluting cars, while the toll is restricted to peak commuters. Toll revenues are now

$$T_p = t_p^* n_p^* = (c+\gamma)\,(n_p^*)^2, \tag{35}$$

with $T_p < T$. Table 3 encapsulates the effect of this policy on the aforementioned five population groups. The main difference of this policy with respect to the application of urban tolls (besides the amount of toll revenues) is found in the absence of the off-peak toll (t_o^*) in the utilities of remaining off-peak drivers and ex-peak drivers.

5.5. Policy comparison

We can now compare the effect of the three alternatives ($tolls$, LEZ, and $comb$) on each population group by looking at Table 3.[52] Tolls are the preferred option for non-drivers and ex-off-peak drivers as they benefit from redistributed toll revenues and the received amount is larger than under $comb$, then $tolls \succ_i comb \succ_i LEZ$ for $i \in (n_t^*, N]$. As for remaining off-peak drivers and ex-peak drivers, their preferred policy is $comb$ because they obtain toll revenues without paying any toll. The comparison between tolls and LEZ for these groups depends on the severity of pollution, which is determined by the threshold $\tilde{\gamma}$. More precisely, whenever the environmental damage is sufficiently severe, i.e., $\gamma > \tilde{\gamma}$, then the cost of paying tolls always exceeds the gain stemming from toll revenues and $T/N < t_o^*$ (even when toll revenues are fully distributed, i.e., $\lambda = 1$). Therefore, $comb \succ_i LEZ \succ_i tolls$ for $i \in (n_p^*, n_t^*]$ whenever $\gamma > \tilde{\gamma}$. Finally, LEZ is the preferred policy for remaining peak drivers as they take advantage of congestion and environmental gains at no cost. Acknowledging that toll revenues are larger under tolls as compared to $comb$ (as $T_p < T$), then $LEZ \succ_i tolls \succ_i comb$ for $i \in [0, n_p^*]$. These results are summarized in the proposition that follows (along with Fig. 4 and the last column of Table 3).

Proposition 3. *Comparing the three alternatives, then*
(i) $LEZ \succ_i tolls \succ_i comb$ *for* $i \in [0, n_p^*]$,
(ii) $comb \succ_i LEZ \succ_i tolls$ *for* $i \in (n_p^*, n_t^*]$ *whenever* $\gamma > \tilde{\gamma}$ *and* $comb \succ_i tolls \succ_i LEZ$ *whenever* $\gamma < \tilde{\gamma}$,
(iii) $tolls \succ_i comb \succ_i LEZ$ *for* $i \in (n_t^*, N]$.

Proof. Provided in Appendix D.

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[51] In a different framework, Basso et al. (2021) consider exemptions to urban tolls for clean cars (e.g., electric vehicles or cars below a certain vintage threshold) during the periods of the year in which local air pollution is of concern. This idea can also be understood as a combination of urban tolls and LEZ.

[52] The status quo (where no policy is applied) is not included in the comparison. The reason is that the comparisons of the aforementioned three policy alternatives with respect to the status quo for the five population groups is complex and yields many ambiguous results. In addition, as mentioned before, the application of policy measures is obliged when the effects of the externalities are severe.

A careful observation of the results in Proposition 3 suggests some interesting observations. Under mild conditions, $comb$ is the most preferred of the three available alternatives for a majority of citizens. Furthermore, voting cycles are also possible.

Corollary 3. *When* $n_p^* < N/2$ *and* $n_o^* > N/2$*, a majority of citizens prefers a combination of urban tolls and LEZ (*$comb$*) over an exclusive implementation of either tolls or* LEZ*.*

From Proposition 3, it follows that a majority of citizens prefers $comb$ over LEZ for $n_p^* < N/2$ while a majority of citizens prefers $comb$ over tolls for $n_o^* = n_t^* - n_p^* > N/2$. This condition requires the amount of remaining peak drivers to be smaller than 50% of the total number of citizens and the amount of off-peak drivers to exceed this threshold. This is a plausible scenario because peak periods are really circumscribed in time (typically, one hour in the morning and another one in the evening). Using a sample of European cities, the European Commission estimates the average number of car commuters per hour to be 1530 during peak periods and 920 during off-peak periods, so that the overall off-peak traffic volume is clearly expected to go beyond the overall peak traffic volume.[53] This result has notable policy implications as a combination of urban tolls and LEZ can be employed to get around the acceptability problem often associated to urban tolls (that are perceived as new taxes) and to stringent LEZ. In fact, this combination of instruments was designed and applied in Milan and Palermo, where a congestion charge is combined with a low emission zone, so that all vehicles meeting the emission standards are requested to pay a fixed daily charge in office hours. London, Stockholm, and Gothenburg started with a congestion charge scheme and adopted LEZ later on.[54] In a different framework, Basso et al. (2021) also consider a combination of price and quantity-based restrictions. They conclude that this hybrid system implies advantages in terms of acceptability as compared to an exclusive implementation of urban tolls.

As observed in Proposition 3, the ordering of alternatives in the preferences of population groups is heterogeneous. In this framework, majority voting among the mentioned alternatives can result into voting cycles, as made clear in the following corollary.

Corollary 4. *With* $\gamma > \tilde{\gamma}$*, majority voting among* $tolls$*,* LEZ*, and* $comb$ *yields cyclical social preferences of the type* $LEZ \succ tolls \succ comb \succ LEZ$ *whenever* $max\left\{n_p^*, n_t^* - n_p^*\right\} < N/2 < n_t^*$*.*

Proof. Provided in Appendix D.

In many urban areas, there is a general agreement among citizens on the need to adopt policy measures to mitigate the negative impact of pollution and congestion. However, the lack of consensus on the precise measure(s) to be adopted can result into long-lasting policy discussions that end up delaying the actual implementation of any measure. The above corollary helps explaining these difficulties in obtaining sufficient support for particular measures. For instance, there has been a long discussion in Barcelona (starting around 2005) on the most convenient measure to be applied, until the approval of a low emission zone in 2019. Despite this decision, the issue is still far from being settled and there is a ongoing discussion on the possibility to modify the current low emission zone and combine it with an urban toll (as in the case of Milan and London).

All in all, the results obtained in this section explain why some cities use of a combination of price and quantity measures while others are embroiled in long-lasting discussions without applying any measure, as encapsulated in *SF*-3 (see Section 2).

6. Public transit

Our baseline model classifies individuals into drivers and non drivers. In this section, we extend the analysis to accommodate two different types of non drivers: those who do not commute at all and those who make use of public transit. This allows assessing the consequences of a more sophisticated use of revenues from urban tolls as they can be used to fund public transit. As previously discussed, subsidizing public transportation is a common practice accompanying traffic restriction policies in many cities to enhance their acceptability.

6.1. Set-up, equilibrium, and social optimum

Public transit can be easily modeled using the set-up introduced in the previous section,[55] letting now subindices p and o denote private and public transportation, respectively. There are two major differences with respect to the previous section. First, using public transit implies a different individual cost as compared to car use, so that $AC_o = \delta d$ with $\delta \in [0, a_o/d]$.[56] Second, using public

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[53] Data from EC (1997).

[54] In the case of Gothenburg, the low emission zone is restricted to trucks and buses.

[55] In a previous paper, De Borger and Proost (2012) analyze the effects of introducing public transit on the acceptability of urban tolls, but their approach embodies a key limitation. They assume a fixed number of users that stay at home and reinterpret consumers' WTP as the generalized cost of public transportation (which is uniformly distributed across users).

[56] Having an upper bound for δ ensures $n_t^e = n_t^* > 0$ (see expression (38)). As $a_o > d$, our model allows for δ smaller or larger than 1. Therefore, public transportation may have a smaller individual cost than car use ($0 < \delta < 1$) or a larger individual cost than car use ($1 < \delta < a_o/d$).

transit does not generate any pollution, so that $MSC_o = AC_o$, while the AC_p and MSC_p expressions remain unaltered.[57] Therefore, equilibrium and social-optimum number of drivers and public transit users is determined by

$$n_p^e = \frac{a_p - a_o - d(1-\delta)}{b_p - b_o + c}, \tag{36}$$

$$n_p^* = \frac{a_p - a_o - d(1-\delta)}{b_p - b_o + 2c + \gamma}, \tag{37}$$

$$n_o^e = n_t^e - n_p^e \text{ and } n_o^* = n_t^* - n_p^*, \text{ with } n_t^e = n_t^* = \frac{a_o - \delta d}{b_o}. \tag{38}$$

Notice that the equilibrium number of public transit users will not be reduced after implementing policies (i.e., $n_t^e = n_t^*$), as they do not generate any externalities. We can also observe that nobody stays at home when public transit is provided at no cost for potential users, i.e., $n_t^e = n_t^* = N = a_o/b_o$ for $\delta = 0$.[58]

6.2. Urban tolls

An optimal urban toll imposed to private-transportation commuters would amount to

$$t_p^* = (c+\gamma)\, n_p^* = \frac{(c+\gamma)\left[a_p - a_o - d(1-\delta)\right]}{b_p - b_o + 2c + \gamma}, \tag{39}$$

and would raise the revenues $T_p = t_p^* n_p^* = (c+\gamma)\left(n_p^*\right)^2$. In line with our previous analysis, we consider that a proportion $\lambda \in [0,1]$ of these revenues is equally distributed over the whole population, i.e., $\lambda T_p/N$. We now organize the population N around four groups: *non-drivers* located in $(n_t^e = n_t^*, N]$, *remaining public transit users* (notice that no public transit user becomes non-driver) located in $(n_p^e, n_t^e = n_t^*]$, *ex-drivers* (that become public transit users) located in $(n_p^*, n_p^e]$, and *remaining drivers* located in $[0, n_p^*]$. Table 4 summarizes in a synthetic way the effect of the considered policies over each group.

As using public transit does not generate any pollution, the environmental gains derived from the implementation of tolls (i.e., $\gamma[(n_p^e)^2 - (n_p^*)^2]/2N$) come exclusively from ex-drivers that become public transit users. Ex-drivers, besides receiving toll revenues and environmental gains, lose the difference in terms of trip valuation between driving and using public transit, i.e., $WTP_p - WTP_o = a_p - a_o - \left(b_p - b_o\right) i$. By contrast, they save the corresponding difference in terms of cost per trip, i.e., $AC_p(n_p^e) - AC_o = d(1-\delta) + cn_p^e$.

6.3. Urban tolls with public transit subsidies

As subsidizing public transportation is a common practice accompanying traffic restriction policies in many cities to enhance their acceptability, it is interesting to analyze the consequences of a tax and subsidy package (that we denote by $tolls{+}sub$). Following De Borger and Proost (2012), optimal tax-subsidy combinations satisfy

$$\tau_p^* + s_o^* = (c+\gamma)\, n_p^*, \tag{40}$$

where the toll revenues can only be used to subsidize public transit and τ_p^* denotes the optimal toll in the presence of public transit subsidies. Therefore, the budget constraint

$$\tau_p^* n_p^* = s_o^* \underbrace{(n_t^* - n_p^*)}_{n_o^*}, \tag{41}$$

needs to be observed. From (40) and (41), it is easy to derive the unique welfare-optimal tax and subsidy package, which is given by

$$s_o^* = \frac{(c+\gamma)\left(n_p^*\right)^2}{n_t^*},$$

$$\tau_p^* = \frac{(c+\gamma)\, n_p^* (n_t^* - n_p^*)}{n_t^*} = (c+\gamma)\, n_p^* - \underbrace{\frac{(c+\gamma)\left(n_p^*\right)^2}{n_t^*}}_{s_o^*}. \tag{42}$$

Therefore, once the toll is implemented, public transit users (i.e., remaining public transit users and ex-drivers) receive the per-capita subsidy s_o^*, while remaining drivers have to pay τ_p^* (results summarized in Table 4).

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[57] It may be argued that public transit generates some local pollution. However, there is a broad consensus in the literature concluding that this effect is clearly lower than the one generated by private transportation (see, e.g., Chen and Whalley, 2012; Fageda, 2021; Gendron-Carrier et al., 2022; Li et al., 2019; Rizzi and De la Maza, 2017; Sen et al., 2010). Assuming that public transit generates some pollution (such that $AC_o < MSC_o < MSC_p$) would not change our results qualitatively, while it would complicate the analysis.

[58] A comparison with the previous section reveals that n_p^e and n_p^* are lower while n_t^e and n_t^* are higher, meaning that $n_o^e = n_t^e - n_p^e$ and $n_o^* = n_t^* - n_p^*$ are now higher, as public transit is cheaper than driving off peak and produces 0-emissions.

Table 4

tolls, *tolls+sub*, and *LEZ* in a model with public transit.

Group	*tolls*	*tolls + sub*	*LEZ*	Ranking
remaining drivers $[0, n_p^*]$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{c(n_p^e-n_p^*)}_{time\ gain} - \underbrace{(c+\gamma)n_p^*}_{toll}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{c(n_p^e-n_p^*)}_{time\ gain} \underbrace{-(c+\gamma)n_p^* + \frac{(c+\gamma)(n_p^*)^2}{n_t^*}}_{toll}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{c(n_p^e-n_p^*)}_{time\ gain}$	$LEZ \succ_i tolls{+}sub \succ_i tolls$
ex−drivers $(n_p^*, n_p^e]$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{d(1-\delta)cn_p^e}_{AC_p-AC_o} - \underbrace{[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o}$	$\underbrace{s_o^*}_{subsidy} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{d(1-\delta)cn_p^e}_{AC_p-AC_o} - \underbrace{[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain} + \underbrace{d(1-\delta)cn_p^e}_{AC_p-AC_o} - \underbrace{[a_p-a_o-\left(b_p-b_o\right) i]}_{WTP_p-WTP_o}$	$tolls\ {+}sub \succ_i tolls \succ_i LEZ$
remaining public transit users $(n_p^e, n_t^e{=}n_t^*]$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{s_o^*}_{subsidy} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$tolls{+}sub \succ_i tolls \succ_i LEZ$
non−drivers $(n_t^e{=}n_t^*, N]$	$\underbrace{\lambda \frac{T_p}{N}}_{toll\ rev.} + \underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$\underbrace{\gamma \frac{(n_p^e)^2-(n_p^*)^2}{2N}}_{environ.\ gain}$	$tolls \succ_i tolls{+}sub \sim_i LEZ$

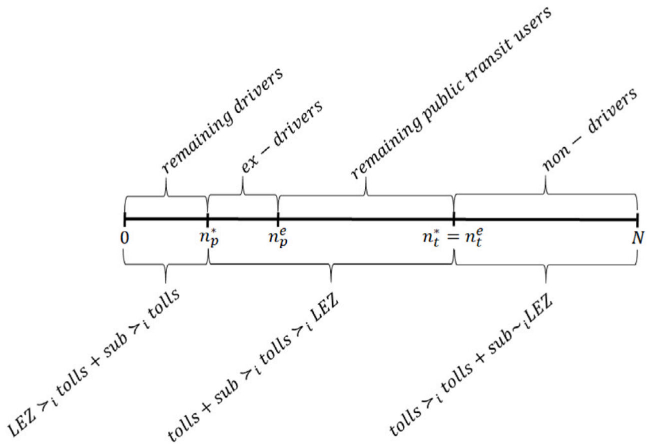

Fig. 5. Policy comparison in a model with public transit.

6.4. LEZ

As public transit produces 0-emissions, LEZ would only concern private transportation by banning vehicles polluting more than γn_p^*. The results of implementing such policy are also encapsulated in Table 4.

6.5. Policy comparison

A comparison between urban tolls and LEZ shows that non-drivers, remaining public transit users, and ex-drivers are better off under tolls as they benefit from redistributed toll revenues. Instead, remaining drivers prefer LEZ to tolls, as they are the only ones paying the tax (and the cost of paying the toll always exceeds the per-capita toll revenues). This result confirms the one reported in Proposition 1 and Corollary 2 (that remains valid after replacing n^* by n_p^*).[59]

Incorporating the alternative $tolls{+}sub$ is straightforward. Given that non-drivers are better off under tolls as compared to LEZ and that they do not receive any toll revenue under $tolls{+}sub$ (because tolls are used to subsidize public transit), then $tolls \succ_i tolls{+}sub \sim_i LEZ$ for $i \in (n_t^e = n_t^*, N]$. As for remaining public transit users and ex-drivers, although they prefer tolls to LEZ due to redistributed toll revenues, they are even better off under $tolls{+}sub$ because the subsidy they receive is larger than toll revenues ($s_o^* > \lambda (c+\gamma)(n_p^*)^2/N$ even when toll revenues are fully distributed, i.e., $\lambda = 1$), so that $tolls{+}sub \succ_i tolls {\succ_i} LEZ$ for $i \in (n_p^*, n_t^e = n_t^*]$. Finally, remaining drivers have to pay under tolls and under $tolls{+}sub$ and, therefore, they are better off under LEZ. They prefer $tolls{+}sub$ to tolls because $\tau_p^* < t_p^* - \lambda T_p/N$, i.e., the redistributed toll revenues do not compensate the difference between tolls. Therefore, $LEZ \succ_i tolls{+}sub {\succ_i} tolls$ for $i \in [0, n_p^*]$. These results are summarized in the proposition that follows (along with Fig. 5 and the last column of Table 4).

Proposition 4. *Comparing the three alternatives, then* $LEZ \succ_i tolls{+}sub {\succ_i} tolls$ *for* $i \in \left[0, n_p^*\right]$, $tolls{+}sub \succ_i tolls {\succ_i} LEZ$ *for* $i \in (n_p^*, n_t^e = n_t^*]$, *and* $tolls \succ_i tolls{+}sub \sim_i LEZ$ *for* $i \in (n_t^e = n_t^*, N]$.

A careful observation of the results in Proposition 4 suggests that using toll revenues to subsidize public transit may enhance the acceptability of tolls, as summarized in the corollary below.

Corollary 5. *Using toll revenues to subsidize public transit enhances the acceptability of tolls among all commuters (remaining drivers, ex-drivers, and remaining public transit users).*

This is a very relevant result that helps explaining the importance of credible commitments to invest in public transit to enhance the acceptability of urban tolls, as suggested in the literature and observed in most cities applying urban tolls (London, Stockholm, Milan, Gothenburg, and Palermo). However, even when toll revenues are used to improve public transit, remaining drivers (who own the newer and less polluting cars) will always prefer LEZ to any other policy including tolls because they benefit from congestion and pollution mitigation at no cost. This explains why price restrictions remain difficult to implement (as there are only five cities in Europe that have effectively applied them) as compared to quantity restrictions (confirming the intuitions already implied by our baseline model in Proposition 1, which is robust to the introduction of public transit). In addition, LEZ are preferred by remaining drivers who do not benefit from investments in public transit, a result that advises against undertaking such investments to improve the acceptability of LEZ. Altogether, these findings provide a foundation for *SF*-4 (see Section 2).

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[59] Interestingly, we could add $\partial n_p^*/\partial \delta > 0$, meaning that LEZ would receive a larger support the more expensive is the public transit ticket because the number of remaining drivers increases when the alternative mode of transportation becomes less attractive.

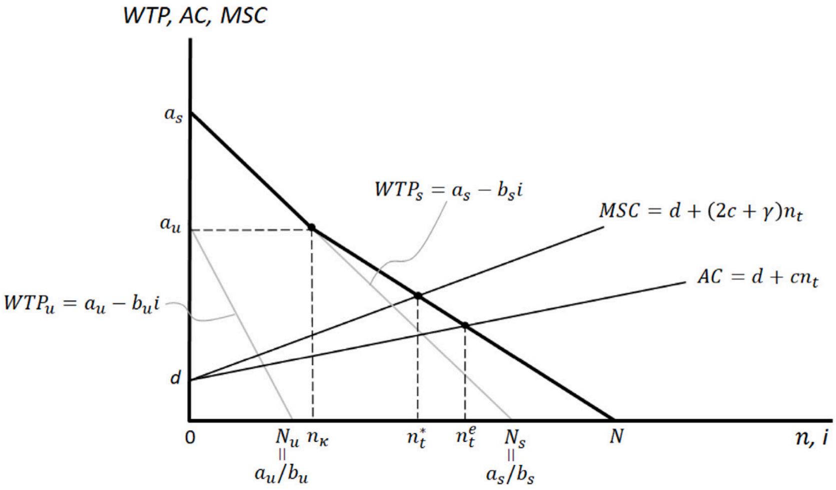

Fig. 6. Heterogeneous commuters.

7. Heterogeneous commuters

Let us consider now the existence of heterogeneous commuters. More precisely, this extension assumes two distinct populations of commuters: individuals living and working in the densely populated urban core (urban residents) and individuals living in less dense suburban areas and commuting to the urban core (suburban residents).

7.1. Set-up, equilibrium, and social optimum

These two groups of individuals are differentiated in terms of WTP and impact of air pollution. Specifically, commuter i's WTP is given by either $WTP_u = a_u - b_u i$ or $WTP_s = a_s - b_s i$, where subscripts u and s denote urban and suburban, respectively. We assume that $a_s > a_u$ because urban residents have more commuting options such as public transit, biking, electric scooters, walking, etc. Therefore, the urban resident with highest WTP is willing to pay less for a trip than the suburban resident with highest WTP. Denoting n_u, n_s, and n_t the number of urban, suburban, and total drivers, respectively, the (aggregate) inverse demand functions for urban and suburban drivers are given by $\rho_u = a_u - b_u n_u$ and $\rho_s = a_s - b_s n_s$, giving rise to the following (kinked) inverse demand function for the overall number of commuting trips

$$\rho_t = \begin{cases} a_s - b_s n_t & \text{for } n_t \in \left[0, n_\kappa\right) \\ \frac{b_u a_s + b_s a_u}{b_s + b_u} - \frac{b_s b_u}{b_s + b_u} n_t & \text{for } n_t \in \left[n_\kappa, N\right] \end{cases}, \tag{43}$$

where $n_\kappa = \frac{a_s - a_u}{b_s}$ identifies the cutoff value for n_t at the kink and $N = N_u + N_s$ is the total number of potential commuters (i.e., both urban and suburban) with $N_u = \frac{a_u}{b_u}$, $N_s = \frac{a_s}{b_s}$, and $b_s > \underline{b}_s \equiv \frac{a_s - a_u}{a_u - d}(2c + \gamma)$.[60]

As before, a vehicle produces polluting emissions given by γi with $\gamma > 0$. Consequently, an urban and a suburban commuter owning cars that produce the same emission level might have different WTPs, and an urban and a suburban commuter with the same WTP might own cars producing different emission levels. The average and marginal social cost of a commuting trip are given by $AC = d + cn_t$ and $MSC = d + (2c + \gamma) n_t$. These AC and MSC functions are represented together with the (kinked) inverse demand function in Fig. 6.[61]

The impact of air pollution over urban and suburban residents is also heterogeneous. Pollution is unequally distributed over the considered jurisdiction, with σ_u and σ_s denoting the share of pollution affecting the urban and suburban areas (with $\sigma_u + \sigma_s = 1$), respectively. Therefore, each urban (suburban) resident supports σ_u/N_u (σ_s/N_s) of the total pollution externality.[62]

The condition $\rho_t = AC$ yields the market equilibrium

$$n_t^e = \frac{b_u\left(a_s - d\right) + b_s\left(a_u - d\right)}{b_s b_u + c\left(b_s + b_u\right)}, \tag{44}$$

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[60] Having a lower bound for b_s ensures that the equilibrium and socially optimal traffic comprises both urban and suburban commuters. The degenerated case without urban commuters converges to the baseline model.

[61] Notice that having heterogeneous consumers in terms of travel time cost (i.e., having $d_u \neq d_s$) would be tantamount to assuming different $WTPs$ because both the market equilibrium and the social optimum number of drivers depend on the gaps $a_u - d$ and $a_s - d$ (see Eqs. (44) and (45)). Therefore, no additional insight would be obtained by introducing this new source of asymmetry.

[62] As city centers are often more polluted than suburbs, $\sigma_u > \sigma_s$ seems a natural assumption. However, this analysis does not require such a restriction.

with $n_s^e = \frac{b_u(a_s-d)+c(a_s-a_u)}{b_s b_u+c(b_s+b_u)}$ and $n_u^e = \frac{b_s(a_u-d)-c(a_s-a_u)}{b_s b_u+c(b_s+b_u)}$, while the socially optimal number of drivers is obtained from $\rho_t = MSC$ and is given by

$$n_t^* = \frac{b_u\left(a_s-d\right)+b_s\left(a_u-d\right)}{b_s b_u+(2c+\gamma)\left(b_s+b_u\right)}, \tag{45}$$

with $n_s^* = \frac{b_u(a_s-d)+(2c+\gamma)(a_s-a_u)}{b_s b_u+(2c+\gamma)(b_s+b_u)}$ and $n_u^* = \frac{b_s(a_u-d)-(2c+\gamma)(a_s-a_u)}{b_s b_u+(2c+\gamma)(b_s+b_u)}$.

7.2. Urban tolls

We now consider a (cordon) urban toll that is charged to suburban commuters when entering (leaving) the city center, so that urban residents do not bear the cost of this policy.[63] Consequently, to achieve the overall optimal number of drivers, the elimination of the excess traffic $(n_t^e - n_t^*)$ is exclusively channeled through a reduction of suburban drivers, while the number of urban drivers remains unaffected. Defining n_u^{toll} and n_s^{toll} the number of urban and suburban drivers after the implementation of tolls, respectively, it follows that $n_u^{toll} = n_u^e$ and $n_s^{toll} = n_t^* - n_u^e$. The optimal toll t^* is obtained from the condition $\rho_s(n_s^{toll}) = AC\left(n_t^*\right) + t^*$ as

$$t^* = \frac{\left(b_s+b_u\right)\left(c+b_s\right)(c+\gamma)}{b_s b_u+c\left(b_s+b_u\right)}\frac{b_u\left(a_s-d\right)+b_s\left(a_u-d\right)}{b_s b_u+(2c+\gamma)\left(b_s+b_u\right)}. \tag{46}$$

Toll revenues are given by

$$T = t^* n_s^{toll} = \frac{\left(b_s+b_u\right)\left(c+b_s\right)(c+\gamma)}{b_s b_u+c\left(b_s+b_u\right)} n_t^*\left(n_t^*-n_u^e\right)\ . \tag{47}$$

Even if tolls are entirely paid by suburban commuters, toll revenues are equally distributed over the whole population of potential commuters in line with our previous analysis.

7.3. LEZ

Differently to tolls that are exclusively charged on suburban commuters, the implementation of LEZ affects equally both urban and suburban commuters owning polluting vehicles that do not comply with the emission standard.

7.4. Policy comparison

In this subsection, we compare the effect of the three alternatives (no policy, tolls, and LEZ) on urban and suburban residents. The population of urban residents is now organized around four groups: *remaining drivers* located in $(0, n_u^*]$, *ex-drivers harmed by* LEZ located in $(n_u^*, \hat{n}_u]$, *ex-drivers benefited by* LEZ located in $(\hat{n}_u, n_u^e]$, and *non-drivers* located in $(n_u^e, N_u]$,[64] where the cutoff value $\hat{n}_u$ that differentiates ex-drivers benefited and harmed by the implementation of LEZ is given by

$$\hat{n}_u = n_u^e - \frac{1}{b_u}\underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain}. \tag{48}$$

On the other hand, the population of suburban residents is organized around five groups: *remaining drivers* located in $\left[0, n_s^*\right]$, *ex-drivers harmed by tolls and* LEZ located in $(n_s^*, \tilde{n}_s]$, *ex-drivers benefited by tolls and harmed by* LEZ located in $(\tilde{n}_s, \hat{n}_s]$, *ex-drivers benefited by tolls and* LEZ located in $(\hat{n}_s, n_s^e]$, and *non-drivers* located in $(n_s^e, N_s]$,[65] where the cutoff values $\tilde{n}_s$ and $\hat{n}_s$ that differentiate ex-drivers benefited and harmed by the implementation of tolls and LEZ, respectively, are given by

$$\tilde{n}_s = n_s^e - \frac{1}{b_s}\left(\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll revenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain}\right), \tag{49}$$

$$\hat{n}_s = n_s^e - \frac{1}{b_s}\underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental gain}. \tag{50}$$

Urban tolls are the preferred policy measure for all urban residents as they receive part of the revenues without having to pay the toll. Moreover, urban residents prefer LEZ to no policy, except for those ex-drivers being characterized by a relatively high WTP.

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[63] Note that, in the case of a toll affecting equally both urban and suburban commuters, the analysis would replicate the baseline model.

[64] The ordering $0 < n_u^* < \hat{n}_u < n_u^e < N_u$ can be established (see Appendix E).

[65] The ordering $0 < n_s^{toll} < n_s^* < \tilde{n}_s < \hat{n}_s < n_s^e < N_s$ can be established (see Appendix E).

Table 5

$tolls$ and LEZ with heterogeneous consumers.

Urban group	$tolls$	LEZ	Ranking
remaining drivers $(0, n_u^*]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain} + \underbrace{c\left(n_t^e-n_t^*\right)}_{time\ \ gain}$	$\underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmentalgain} + \underbrace{c\left(n_t^e-n_t^*\right)}_{time\ \ gain}$	$tolls \succ_i LEZ \succ_i \varnothing$
ex-drivers harmed by LEZ $(n_u^*, \widehat{n}_u]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_u-b_u i\right)}_{WTP}$	$\underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_u-b_u i\right)}_{WTP}$	$tolls \succ_i \varnothing \succ_i LEZ$
ex-drivers benefited by LEZ $(\widehat{n}_u, n_u^e]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_u-b_u i\right)}_{WTP}$	$\underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_u-b_u i\right)}_{WTP}$	$tolls \succ_i LEZ \succ_i \varnothing$
non-drivers $(n_u^e, N_u]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{tollrevenue} + \underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{tenvironmental\ \ gain}$	$\underbrace{\sigma_u\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_u}}_{environmental\ \ gain}$	$tolls \succ_i LEZ \succ_i \varnothing$
Suburban group	$tolls$	LEZ	Ranking
remaining drivers $\left[0, n_s^*\right]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{c\left(n_t^e-n_t^*\right)}_{time\ \ gain} - \underbrace{t^*}_{toll}$	$\underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{c\left(n_t^e-n_t^*\right)}_{time\ \ gain}$	$LEZ \succ_i \varnothing \succ_i tolls$
ex-drivers harmed by tolls and LEZ $(n_s^*, \widetilde{n}_s]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$\underset{environmental\ \ gain}{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$\varnothing \succ_i tolls \succ_i LEZ$
ex-drivers benefited by tolls and harmed by LEZ $(\widetilde{n}_s, \widehat{n}_s]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$\underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$tolls \succ_i \varnothing \succ_i LEZ$
ex-drivers benefited by tolls and LEZ $(\widehat{n}_s, n_s^e]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{toll\ \ revenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$\underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain} + \underbrace{\left(d+cn_t^e\right)}_{AC\left(n_t^e\right)} - \underbrace{\left(a_s-b_s i\right)}_{WTP}$	$tolls \succ_i LEZ \succ_i \varnothing$
non-drivers $(n_s^e, N_s]$	$\underbrace{\lambda\frac{t^* n_s^{toll}}{N}}_{tollrevenue} + \underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain}$	$\underbrace{\sigma_s\gamma\frac{\left(n_t^e\right)^2-\left(n_t^*\right)^2}{2N_s}}_{environmental\ \ gain}$	$tolls \succ_i LEZ \succ_i \varnothing$

Therefore, $tolls \succ_i LEZ \succ_i \varnothing$ for $i \in (0, n_u^*]$ and $i \in (\widehat{n}_u, N_u]$ and $tolls \succ_i \varnothing \succ_i LEZ$ for $i \in (n_u^*, \widehat{n}_u]$. As regards to suburban residents, the analysis replicates the one carried out in the baseline model, so that $LEZ \succ_i \varnothing \succ_i tolls$ for $i \in (0, n_s^*]$, $\varnothing \succ_i tolls \succ_i LEZ$ for $i \in (n_s^*, \widetilde{n}_s]$, $tolls \succ_i \varnothing \succ_i LEZ$ for $i \in (\widetilde{n}_s, \widehat{n}_s]$, and $tolls \succ_i LEZ \succ_i \varnothing$ for $i \in (\widehat{n}_s, N_s]$. The details on the effects of tolls and LEZ over urban and suburban residents can be found in Table 5. The results of this policy comparison are summarized in the proposition below and illustrated in Fig. 7.

Proposition 5. *Comparing the three alternatives, then*
(i) $LEZ \succ_i \varnothing \succ_i tolls$ *for* $i \in \left[0, n_s^*\right]$,
(ii) $\varnothing \succ_i tolls \succ_i LEZ$ *for* $i \in (n_s^*, \widetilde{n}_s]$,
(iii) $tolls \succ_i \varnothing \succ_i LEZ$ *for* $i \in (\widetilde{n}_s, \widehat{n}_s]$ *and* $i \in (n_u^*, \widehat{n}_u]$,
(iv) $tolls \succ_i LEZ \succ_i \varnothing$ *for* $i \in (\widehat{n}_s, N_s]$, $i \in (0, n_u^*]$, *and* $i \in (\widehat{n}_u, N_u]$.

As compared to Proposition 1 from the baseline model, the main difference is found in the existence of a new group of urban residents that live and commute within the restricted area and, therefore, do not have to pay cordon tolls. The above proposition has the following implications when considering the implementation of either tolls or LEZ under majority voting. On the one hand, a pairwise comparison between $\varnothing$ and tolls indicates that tolls are preferred by the share $N_s - \widetilde{n}_s$ of suburban residents and the whole population N_u of urban residents, which is tantamount to $N - \widetilde{n}_s$ residents. On the other hand, the pairwise comparison between $\varnothing$ and LEZ suggests that LEZ are preferred by $N_s - \widehat{n}_s + n_s^*$ suburban residents and $N_u - \widehat{n}_u + n_u^*$ urban residents, which is tantamount to $N - \left(\widehat{n}_u - n_u^*\right) - \left(\widehat{n}_s - n_s^*\right)$ residents. This gives rise to the following corollary.

Corollary 6. *Departing from the status quo (i.e., no policy),* LEZ *are easier to implement than tolls whenever the number of individuals being harmed by tolls exceeds the number of individuals being harmed by* LEZ, *i.e.,* $\widetilde{n}_s > \left(\widehat{n}_u - n_u^*\right) + \left(\widehat{n}_s - n_s^*\right)$.

This result deviates from the unambiguous finding in Corollary 1 suggesting that LEZ are always easier to implement. This is explained by the presence of urban residents that always prefer tolls to LEZ. More precisely, now there are two differentiated types of remaining drivers: the suburban remaining drivers that prefer LEZ to tolls as in the baseline model, and the urban remaining drivers that prefer cordon tolls to LEZ as they commute within the restricted area.

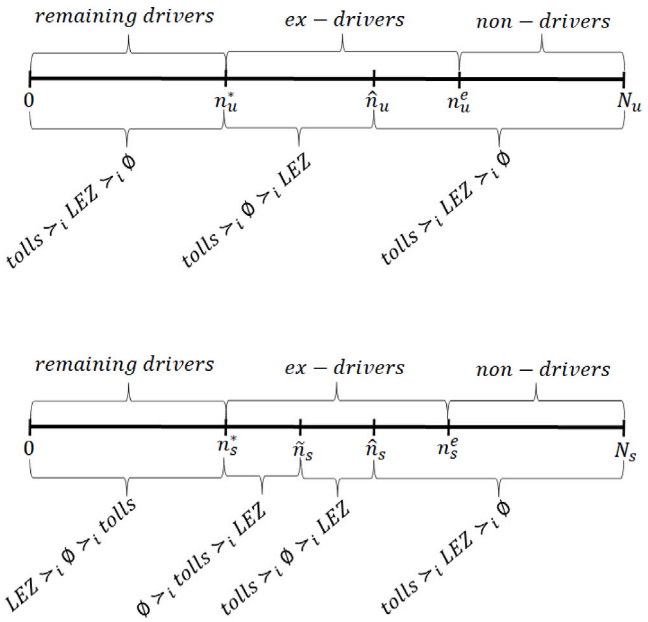

Fig. 7. Policy comparison in a model with heterogeneous commuters.

Considering the choice between the two policy measures, the following corollary can be formulated.

Corollary 7. *Comparing optimal urban tolls and LEZ, there is a majority in favor of LEZ for $n_s^* > N/2$.*

As compared to Corollary 2, now, only the group of suburban remaining drivers would vote in favor of LEZ as urban remaining drivers do not pay the toll.

All in all, a comprehensive assessment of the results in this section suggests that, in a more sophisticated setting with heterogeneous population groups, LEZ are not always better accepted than urban tolls. However, the main insight from the baseline model remains in the sense that LEZ are preferred by those high-income remaining drivers who pay the cordon toll.

Additionally, while the acceptability of cordon tolls is enhanced among urban commuters, this comes at the expense of an increased opposition among suburban commuters as they must bear the entire cost of the toll. Ultimately, the number of urban and suburban residents depends on the boundaries of the restricted area. A larger restricted area increases the number of urban residents not affected by cordon tolls but also the burden of tolls levied on suburban commuters. This tradeoff imposes a *natural* limit on the size of restricted areas for local authorities (e.g., the cordon-toll area represents 1.3% of the overall urban area in London and 9.2% in Stockholm).[66] This insight provides further support to the combination of price and quantity measures spelled out in *SF*-3 (see Section 2) and modeled in Section 5.

A final caveat has to do with the boundary of local jurisdictions delimiting the population having the right to vote. Our model assumes that all residents (urban and suburban) have the right to vote. In the case that only urban residents would have the right to vote, meaning that suburban commuters dwell outside the jurisdiction, voters would have more incentives to support cordon tolls levied on suburban commuters.

8. Discussion

Despite the extensions of our baseline model covered in the previous sections, some concerns may still arise about the generality of the present analysis. This section offers a discussion that calls into question some of its main assumptions.

First, although there is no doubt about the strong correlation between congestion and pollution, it could be argued that tolls are more effective in mitigating congestion as they focus on the number of drivers while LEZ are more effective in curbing pollution as they focus on the composition of the fleet. The proposed set-up assumes an inverse relationship between WTP and vehicle emissions, so that both policy instruments can efficiently eradicate both externalities simultaneously. Our baseline model could be adapted to allow for a dissociation between WTP and vehicle emissions by classifying *initial drivers* in a discrete manner in terms of their WTP (WTP_{high}/WTP_{low}) and their vehicle emission level ('clean'/'dirty'). This gives rise to five differentiated population groups: (i) WTP_{high} drivers owning clean cars, (ii) WTP_{high} drivers owning dirty cars, (iii) WTP_{low} drivers owning clean cars, (iv)

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[66] See Albalate and Bel (2009).

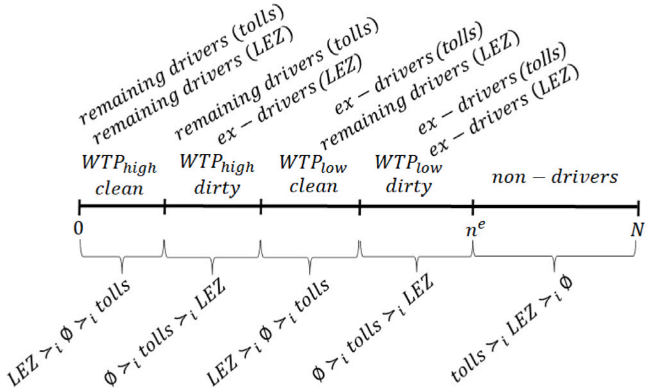

Fig. 8. Policy comparison when *WTP* and car emissions are dissociated.

WTP_{low} drivers owning dirty cars, and (v) non-drivers. In this context, tolls would affect WTP_{low} commuters thereby mitigating congestion, whereas LEZ would affect owners of dirty cars thereby curbing pollution. Neither tolls nor LEZ can therefore deal with both externalities at the same time efficiently, as tolls would leave some dirty cars circulating while LEZ would ban some WTP_{high} commuters from entering the city center. The acceptability of either tolls or LEZ among the aforementioned population groups is summarized in Fig. 8.[67]

As shown in Fig. 8, the policy preferences are driven by vehicle emissions and not by commuters' WTP. Owners of clean cars are always benefited by LEZ and harmed by tolls. Instead, owners of dirty cars are harmed by both tolls and LEZ (but to a greater extent by LEZ). Finally, non-drivers are benefited by both tolls and LEZ (but to a greater extent by tolls). Consequently, our result pointing out that LEZ are more acceptable than tolls (see Corollary 1) remains valid because, departing from the status quo (i.e., no policy), owners of clean cars and non-drivers become better off under LEZ, while only non-drivers become better off under tolls.

Second, our model does not contemplate any effect of price and quantity schemes on the car market. Although incorporating a car market into our analysis would have an effect on payoffs, it would not affect the size of the population groups (remaining drivers, ex-drivers, and non-drivers) because commuting decisions are fundamentally determined by individuals' WTP and, consequently, it would seem unnatural to consider lower-WTP individuals purchasing second-hand cars from higher-WTP individuals to become commuters after some new restrictions are implemented. In addition, the presence of a car market would not have a differentiated impact on these population groups under each of the considered traffic restrictions. All in all, our analysis on the acceptability of price versus quantity restrictions would remain unaltered.

Third, our model abstracts away from potential congestion problems in public transportation derived from an increased use as a consequence of traffic restrictions. Such an extension would eventually change the size and payoffs of some population groups. Specifically, some public transit users might become non-drivers and some initial drivers could decide not to switch to public transit. However, this additional complication would not modify the acceptability of price versus quantity restrictions within these groups (because they would still prefer tolls to LEZ).

Fourth, our model assumes that remaining drivers benefit equally from time gains associated with traffic-reduction measures, while heterogeneity arises from individuals' WTP for commuting trips. Alternatively, commuters' time gains could be also heterogeneous and positively correlated to their respective WTPs. This possible extension would increase the acceptability of both price- and quantity-based measures equally and,[68] consequently, it would have no effect in terms of their relative acceptability.

Fifth, our model assumes that all citizens can react to new traffic restrictions by adjusting their commuting behavior. Of course, some commuters could be insensitive to any restrictive measure. For instance, low-income individuals may be characterized by lower job flexibility, preventing them to switch from peak to off-peak periods. This circumstance could be easily accommodated by incorporating a fraction of initial drivers that would always remain commuting irrespective of the application of any restriction (i.e., this fraction of commuters would always belong to the group of remaining peak drivers). Therefore, this kind of extension would only resize the groups identified in our analysis and, overall, our results would remain qualitatively valid.

Sixth, the approach in this paper focuses on short-run effects because they are dominant in electoral processes, either because voters are not fully foresighted or because they discount significantly potential future payoffs. Taking into consideration the long-run advantage associated to vintage-specific quantity restrictions derived from the changes in the fleet composition toward cleaner cars (Barahona et al., 2020), would enhance the acceptability of such quantity restrictions without changing our results qualitatively.

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[67] This figure focuses on the case in which ex-drivers prefer to remain commuting after the implementation of either $tolls$ or LEZ. This is tantamount to assuming that the WTP gap, defined as $WTP_{high} - WTP_{low}$, is sufficiently small.

[68] This can be easily observed by comparing expressions (11) and (15).

Finally, it could be argued that, once the car fleet becomes fully electric (thereby producing 0-combustion emissions locally),[69] vintage-specific quantity restrictions become ineffective turning the choice between price and quantity schemes immaterial. However, the European Environmental Agency warns that 46% of pollutants generated by private transportation are generated by the so-called *abrasion emissions*, which are produced from the mechanical abrasion and corrosion of vehicle parts (such as the vehicle's tires, brakes, and clutch; the road surface wear; or the corrosion of the chassis, bodywork, and other vehicle components).[70] Consequently, in this future scenario, quantity restrictions will remain effective in curbing pollution as long as they become dissociated from car vintage (because abrasion emissions are independent of vintage) and relate to other vehicle characteristics such as weight or size. Therefore, our analysis on the acceptability of price versus quantity schemes would remain fully valid.

9. Conclusion

Quantity restrictions receive a much larger support than price schemes. Our paper provides a solid background to understand the prevalence of quantity over price mechanisms along with some stylized facts observed in urban areas applying traffic restrictions, such as the implementation of hybrid price-and-quantity systems, the use of trial periods, the commitments from local governments to invest in public transit to enhance the acceptability of urban tolls, and the concentration of quantity restrictions in high-income cities.

Vintage-specific quantity restrictions favor high-income citizens that own the newer and less polluting cars, as they are not affected by the new regulation and take advantage of the resulting congestion and pollution mitigation. Therefore, the relative importance of this group of citizens can have a decisive effect in the acceptability of such restrictions. In addition, this social support will be amplified as initial commuters overestimate the positive effects of quantity schemes (while they underestimate the positive effect of price systems). Taking this information into account, local policy makers may wonder about the regressive effects of quantity restrictions.

Price schemes might effectively mitigate pollution and congestion and be more redistributive, especially when toll revenues are used to subsidize public transit. Their unpopularity, which comes from the fact that they are perceived as new taxes, could be partially relieved by setting up trial periods that would allow the citizens to understand the true effect of the measure, thereby toning down their overpessimistic initial perception.

An alternative, pragmatic, and powerful solution could imply the application of hybrid systems combining quantity and price systems that can potentially receive a larger support than pure price or quantity schemes. However, the resistance to price-based restrictions would still remain an issue in this hybrid case.

Appendix A. Regression analysis

This appendix provides the details of our regression analysis.

A.1. Data

Our sample contains information from urban areas in the EU and the UK with a population exceeding 300,000 inhabitants over the period 2008–2020. The sample of cities is determined by the availability of congestion and pollution data. More precisely, our sample has 1669 observations, with information for 130 cities from 19 different countries.

The most commonly applied emission standard (especially in German cities) is Euro 4 for diesel cars and Euro 1 for gasoline cars.[71] However, some LEZ cities impose tighter requirements. The size of the restricted area also varies across cities. While there are few LEZ cities where the restricted area includes most of the city (such as Barcelona, Paris, Rome or Milan), the usual practice is to establish a restricted area around the city center and the surrounding districts. Nevertheless, this heterogeneity is not a serious concern for our purposes given that our regression analysis relies on a sufficient number of LEZ and non-LEZ cities.

The dependent variable D^{LEZ} is constructed using data provided by CLARS (2020) along with data on city regulations searched online.[72] The urban per-capita income ($INCOME$) is measured at the NUTS-3 level (Eurostat, 2020). Income inequality ($IN-EQUALITY$) is measured at the country level (Eurostat, 2020). Data on polluting emissions ($POLLUTION$) is based on annual mean estimates of PM2.5, i.e., particular matter having aerodynamic diameters smaller or equal to 2.5 μm.[73] These data rely on the method outlined in Van Donkelaar et al. (2019) and we focus on the European subset that provides estimates between 33 and 80 degrees North and −15 and 45 degrees East, at 0.1×0.1 degree resolution (about 10×10 km). In cities having more than one measurement point within the limits of the city, we select the one located closest to the city center. Data on congestion

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[69] Urban policies focus on local emissions, thereby neglecting environmental externalities affecting other locations in the processes of electricity generation and manufacturing of car components (electronic devices, batteries, etc.).

[70] See EEA (2019).

[71] Although some of the first German and Italian LEZ exclusively banned diesel cars, the emission standards in recent years for most LEZ cities include both diesel and gasoline cars. Currently, only few LEZ cities (such as Rotterdam, Utrecht or Athens) ban exclusively diesel cars.

[72] CLARS is the acronym of *Charging, Low Emission Zones, other Access Regulation Schemes*, a website promoted by the European Commission and built by Sadler Consulting.

[73] PM2.5 is one of the most important pollutants because it penetrates into sensitive regions of the respiratory system and can cause or aggravate cardiovascular and lung diseases.

Table A.1
Descriptive statistics.

Variable	Measurement	Source	Mean (LEZ cities)	Mean (non-LEZ cities)	T-Test (diff. in means)
D^{LEZ}	Dummy = 1 in the implementation year and observations from this year onward are dropped, otherwise 0	CLARS (2020)	0.16	0	Non applicable
INCOME	Thousands of euros per inhabitant at the NUTS 3 level	Eurostat (2020)	43.79	29.59	−19.93***
POLLUTION	PM 2.5. in μg/m^3 as the average annual value at the city level	Van Donkelaar et al. (2019)	16.29	13.62	−10.04***
CONGESTION	Excess travel time in percentage in relation to free flow conditions at the city level	TomTom (2020)	25.21	25.33	0.30
DENSITY	Hundreds of inhabitants per square kilometer at the city level	Eurostat (2020)	41.49	34.38	−4.39***
PUBLIC	Number of kilometers of local rail lines per hundreds of thousands of inhabitants at the city level	World Metro Database (2020)	3.21	1.63	−8.71***
CARS	Number of passenger cars per tens of thousands of inhabitants at the NUTS 2 level	Eurostat (2020)	52.99	50.09	−7.36***
INEQUALITY	Ratio of the average income of the top 20% to the bottom 20% in the income distribution at the country level	Eurostat (2020)	5.00	5.02	0.58
IDEOLOGY	Dummy = 1 if city mayor affiliated to a left-wing part, 0 otherwise (i.e., if mayor affiliated to another party, independent or non-elected)	Wikipedia and websites of city councils	0.65	0.35	−11.63***

($CONGESTION$) from TomTom (2020) measures the additional travel time a vehicle needs to undertake a trip in a certain city as compared to a free-flow situation. 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. The congestion index is built in the following way. First, baseline travel times are 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.[74] Finally, baseline and 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.

The population density ($DENSITY$) is the number of inhabitants per square kilometer at the city level, where population data is obtained from Eurostat (2020) and city size is obtained from each city council's website. As data for urban buses are not available, the proxy for the quality of public transportation networks ($PUBLIC$) is a comprehensive measure of the urban rail systems in terms of total kilometers of rail lines per inhabitant, which includes metro, light trains, trams, and local trains (World Metro Database, 2020). The number of registered cars per inhabitant ($CARS$) is measured at the NUTS-2 level (Eurostat, 2020). Finally, there is the dummy that takes the value 1 when the mayor of the city is affiliated in a left-wing party while that it takes the vale 0 otherwise ($IDEOLOGY$), which includes right-wing, non-affiliated, and non-elected mayors (data on the identity of mayors from Wikipedia and data on the ideology of the party in which the mayor is affiliated from each party's official website).[75] Naturally, omitted variables may be an issue, which cannot be fully addressed given the nature of our data. However, omitted variables should not invalidate our results qualitatively because of the following reasons. First, the inclusion of country fixed effects accounts for cross-country heterogeneity (and does not produce any relevant alteration in our estimates as observed in Tables 2 and A3). Second, the influence of other omitted factors on the adoption of LEZ, such as the sectorial composition or the geographic characteristics of restricted areas, is partly channeled through the pollution and congestion variables included in our regression.

Table A.1 shows the descriptive statistics of the variables and the correlation matrix is provided as supplementary material (see Table S1). On average, LEZ cities are richer and denser than non-LEZ cities. Furthermore, LEZ cities are more polluted but not more congested than non-LEZ cities. LEZ cities have a denser rail network and more cars per inhabitant. LEZ do not seem to be adopted in more unequal countries and they are more usually implemented by left-wing parties.

A.2. Additional results

Regressions for the subperiod 2008-2017. Although the considered period is 2008–2020, data for most of explanatory variables are not available for recent years. More precisely, data for $INCOME$, $INEQUALITY$, $DENSITY$, $PUBLIC$, and $CARS$ are available up to 2018. Data for $CONGESTION$ are available up to 2019 and for $POLLUTION$ up to 2016. We therefore use data of the

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[74] 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.

[75] There are non-elected mayors in some English and Irish cities.

Table A.2
Results of estimates-country fixed effects.

Country	Dependent variable: D^{LEZ}
Belgium	1.067** (0.532)
Czech Republic	1.801*** (0.590)
France	−0.778 (0.774)
Germany	2.514*** (0.509)
Greece	0.333 (1.149)
Italy	2.486*** (0.733)
The Netherlands	1.124** (0.569)
Poland	0.823 (0.887)
Portugal	2.346*** (0.668)
Spain	0.817 (0.692)
Sweden	0.808 (0.511)
R^2	0.36
Observations	1075

Notes: Reported results from probit estimations including all covariates and year and country fixed effects. Standard errors in parentheses (robust to heteroscedasticity and clustered at the city level). Statistical significance at 1% (***), 5% (**), 10% (*). The base country is the UK. Cities from Austria, Denmark, Finland, Hungary, Ireland, Romania, and Slovakia are dropped due to lack of variability in terms of LEZ/non-LEZ cities.

most recent year for later years and, to test the sensitivity of our results to this imputation of missing values, we also run regressions for the subperiod 2008–2017. As it turns out, the results do not change qualitatively neither in terms of significance nor size.[76]

Estimated country-fixed effects. Table A.2 shows the estimated country fixed effects that are not presented in Table 2. Controlling for the other variables, LEZ are more likely to be implemented in Germany, Italy and, to a lower extent, in Belgium and The Netherlands. Although Table A.2 suggests a similar conclusion for Portugal and Czech Republic, we should recall that there is just one city in the sample from these two countries (Lisbon and Prague, respectively). Omitted factors at the country level such as the environmental awareness of the population, the role of green parties, neighboring effects across cities or the weight of the car industry may explain differences across countries beyond city attributes.

Marginal effects. Fig. A.1 reports the marginal effects of $INCOME$, $POLLUTION$, and $CONGESTION$ using the regressions with all covariates and country fixed effects. Concerning $INCOME$, we generate the predicted probabilities for values from €10,000 to €90,000 per inhabitant, considering increments of €10,000 (the range of values is based on the minimum and maximum values in our sample). The values in Figure A1 are average predicted probabilities computed using the sample values of the other explanatory variables. As to $POLLUTION$, we generate the predicted probabilities for values of PM2.5 emissions between 5 μg/m^3 and 30 μg/m^3, considering increments of 5 μg/m^3 (as before, the range of values is based on the minimum and maximum values in our sample). Regarding $CONGESTION$, we compute the predicted probabilities for values from 10% to 60% excess travel time, considering increments of 10%.

Higher values of $INCOME$, $POLLUTION$, and $CONGESTION$ lead to increases in the mean predicted probability for LEZ adoption, but Figure A1 clearly shows that the curve is much steeper for $INCOME$ as compared to $POLLUTION$ and $CONGESTION$. In addition, to assess whether the marginal effects increase significantly with the level of $INCOME$, $POLLUTION$, and $CONGESTION$, respectively, we look at the differences between the estimated marginal effects at the lowest and highest measurement interval.

Concerning $INCOME$, the mean predicted probability for LEZ adoption is around 0.03 when urban income is €10,000, while it increases to around 0.40 for cities with an income of €90,000. This difference is significant at the 95% confidence level. As to $POLLUTION$, the mean predicted probability for LEZ adoption is around 0.08 when PM2.5 emissions are 5 μg/m^3,

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[76] Details on these estimation results are provided as supplementary material (see Tables S2 and S3).

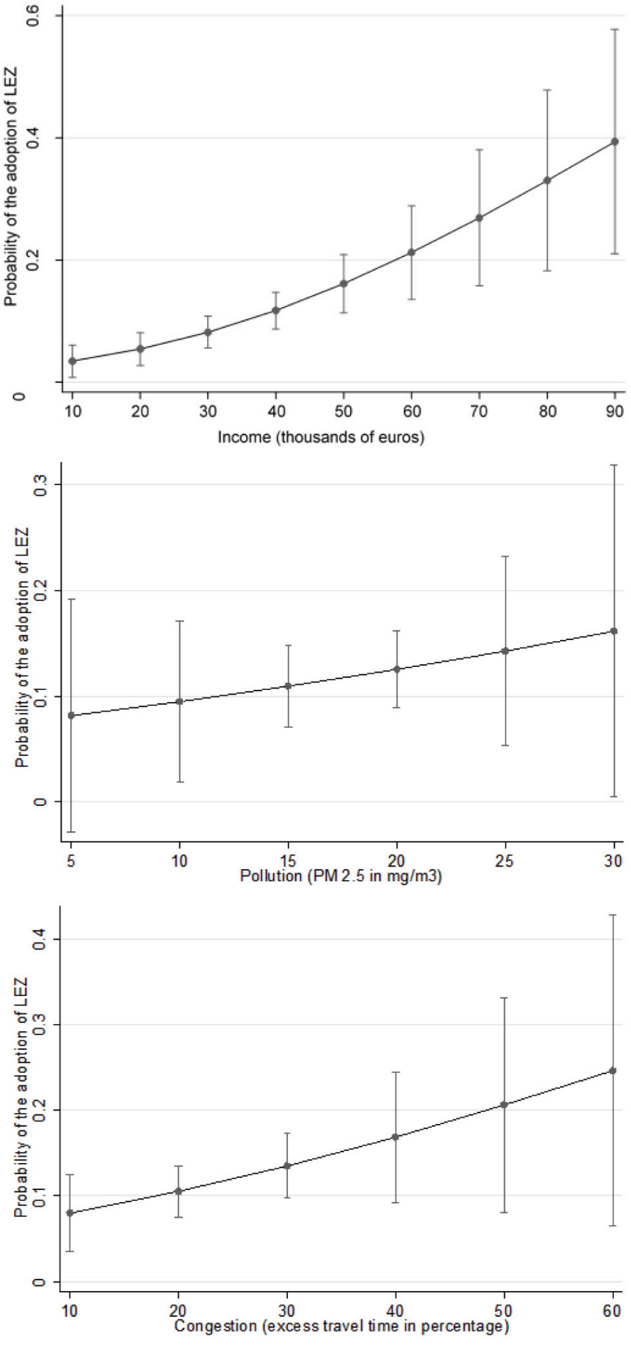

Fig. A.1. Marginal effects of $INCOME$, $POLLUTION$, and $CONGESTION$ (results from probit regressions with all covariates and country fixed effects; confidence interval at 95%).

becoming around 0.16 for emissions of 30 μg/m^3. This difference is non significant at the 95% confidence level. Finally, regarding $CONGESTION$, the mean predicted probability for LEZ adoption is around 0.08 when excess travel time is 10%, while it becomes around 0.25 when excess travel time is 60%. Again, this difference is non significant at the 95% confidence level.

Thus, the mean predicted probability for LEZ adoption is significantly higher (more than 10 times) when we move from minimum to maximum $INCOME$ values. Instead, the mean predicted probability for LEZ adoption is not significantly different between the minimum and the maximum values of $POLLUTION$ and $CONGESTION$. We conclude that the $INCOME$ variable has the highest explanatory power among these regressors in the implementation of LEZ.

Appendix B. Ordering of n^*, $\tilde{n}$, $\hat{n}$, n^e (baseline)

Claim 1. *The following ordering can be established:* $0 < n^* < \tilde{n} < \hat{n} < n^e < N$.

Proof. First, notice that $n^* < \tilde{n}$ requires

$$\tilde{n} - n^* = n^e - n^* - \frac{1}{b}\left(\frac{t^* n^*}{N} + \gamma \frac{(n^e)^2 - (n^*)^2}{2N}\right) > 0. \tag{B.1}$$

Using (6), (7), and $\underline{b} = \gamma(a-d)/d$, (B.1) can be rewritten as

$$\tilde{n} - n^* = \frac{(c+\gamma)(a-d)\left(2c^2(a+d) + 2b^2 d + bd\gamma + 2cd\gamma + 2abc + 3bcd + (c+\gamma)d\left(b - \underline{b}\right)\right)}{2a(b+c)^2(b+2c+\gamma)^2},$$

which is always positive. Second, $\tilde{n} < \hat{n} < n^e$ follows immediately from inspection of (13) and (17). Finally, $0 < n^*$ and $n^e < N$ are always observed (see (6) and (7)). ■

Appendix C. Equilibrium and socially-optimal number of peak and off-peak drivers

C.1. Equilibrium number of peak drivers

Claim 2. $WTP_p - AC_p \geqslant 0$ *and* $WTP_p - AC_p \geqslant WTP_o - AC_o$ *are observed for* $i \in [0, n_p^e]$, *where* n_p^e *is implicitly determined by the second inequality, i.e.,*

$$WTP_p(n_p^e) - AC_p(n_p^e) = WTP_o(n_p^e) - AC_o(n_p^e). \tag{C.1}$$

Proof. From (C.1) we obtain

$$n_p^e = \frac{a_p - a_o}{b_p - b_o + c}$$

such that

$$WTP_p - AC_p(n_p^e) = a_p - b_p i - d - cn_p^e = \frac{\gamma\left(a_p - a_o\right) + \left(b_p - \underline{b}_p\right)\left(a_o - d\right)}{b_p - b_o + c} + b_p\left(n_p^e - i\right) \geqslant 0 \quad \forall i \in [0, n_p^e]$$

and

$$\left[WTP_p - AC_p(n_p^e)\right] - \left[WTP_o - AC_o(n_p^e)\right]$$
$$= a_p - b_p i - d - cn_p^e - \left(a_o - b_o i - d\right) = \left(b_p - b_o\right)\left(n_p^e - i\right) \geqslant 0 \quad \forall i \in [0, n_p^e]. \quad ■$$

C.2. Equilibrium number of off-peak drivers

Claim 3. $WTP_o - AC_o \geqslant 0$ *and* $WTP_o - AC_o \geqslant WTP_p(i) - AC_p$ *are observed for* $i \in (n_p^e, n_t^e]$, *where* n_t^e *is implicitly determined by the first inequality, i.e.,*

$$WTP_o(n_t^e) - AC_o(n_t^e) = 0. \tag{C.2}$$

Proof. From (C.2) we obtain

$$n_t^e = \frac{a_o - d}{b_o}$$

such that

$$\left[WTP_o - AC_o(n_t^e)\right] - \left[WTP_p - AC_p(n_t^e)\right] = a_o - b_o i - d - \left(a_p - b_p i - d - cn_t^e\right)$$
$$= \frac{\gamma\left(a_p - a_o\right) + \left(a_o - d\right)\left(b_p - \underline{b}_p\right)}{b_o\left(c - b_o + b_p\right)} c + \left(b_p - b_o\right)\left(i - n_p^e\right) > 0 \quad \forall i \in (n_p^e, n_t^e]$$

and

$$WTP_o - AC_o(n_t^e) = b_o\left(n_t^e - i\right) > 0 \quad \forall i \in (n_p^e, n_t^e]. \quad ■$$

C.3. Socially-optimal number of peak drivers

Claim 4. *$WTP_p - MSC_p \geqslant 0$ and $WTP_p - MSC_p \geqslant WTP_o - MSC_o$ are observed for $i \in [0, n_p^*]$, where n_p^* is implicitly determined by the second inequality, i.e.,*

$$WTP_p(n_p^*) - MSC_p(n_p^*) = WTP_o(n_p^*) - MSC_o(n_p^*). \tag{C.3}$$

Proof. From (C.3) we obtain

$$n_p^* = \frac{a_p - a_o}{b_p - b_o + 2c}$$

such that

$$\begin{aligned} &WTP_p - MSC_p(n_p^*) \\ &= a_p - b_p i - d - (2c + \gamma)\, n_p^* = \frac{c(a_o - d) + (a_o - d)\left(b_p - \underline{b}_p\right)}{b_p - b_o + 2c} + b_p \left(n_p^* - i\right) \geqslant 0 \quad \forall i \in [0, n_p^*] \end{aligned}$$

and

$$\begin{aligned} &\left[WTP_p - MSC_p(n_p^*)\right] - \left[WTP_o - MSC_o(n_p^*)\right] \\ &= a_p - b_p i - d - (2c + \gamma)\, n_p^* - \left(a_o - b_o i - d - \gamma n_p^*\right) = \left(b_p - b_o\right)\left(n_p^* - i\right) \geqslant 0 \quad \forall i \in [0, n_p^*]. \quad \blacksquare \end{aligned}$$

C.4. Socially-optimal number of off-peak drivers

Claim 5. *$WTP_o - MSC_o \geqslant 0$ and $WTP_o - MSC_o \geqslant WTP_p - MSC_p$ are observed for $i \in (n_p^*, n_t^*]$, where n_t^* is implicitly determined by the first inequality, i.e.,*

$$WTP_o(n_t^*) - MSC_o(n_t^*) = 0. \tag{C.4}$$

Proof. From (C.4) we obtain

$$n_t^* = \frac{a_o - d}{b_o + \gamma}$$

such that

$$\begin{aligned} &\left[WTP_o - MSC_o(n_t^*)\right] - \left[WTP_p - MSC_p(n_t^*)\right] \\ &= a_o - b_o i - d - \gamma n_t^* - \left(a_p - b_p i - d - (2c + \gamma)\, n_t^*\right) \\ &= 2c \frac{\left(b_p - \underline{b}_p\right) + c}{(\gamma + b_o)\left(b_p - b_o + 2c\right)} \left(a_o - d\right) + \left(b_p - b_o\right)\left(i - n_p^*\right) > 0 \quad \forall i \in (n_p^*, n_t^*] \end{aligned}$$

and

$$WTP_o - MSC_o(n_t^*) = b_o \left(n_t^* - i\right) \geqslant 0 \quad \forall i \in (n_p^*, n_t^*]. \quad \blacksquare$$

C.5. Ordering of n_p^e, n_t^e, n_p^*, n_t^*

Claim 6. *The following ordering can be established:* $0 < n_p^* < n_p^e < n_t^* < n_t^e < N$.

Proof. First, notice that

$$n_p^* = \frac{a_p - a_o}{b_p - b_o + 2c} = \frac{a_p - a_o}{b_p - \underline{b}_p + \left(\gamma + b_o\right) \frac{a_p - a_o}{a_o - d} + c} > 0,$$

which proves the first inequality. Next,

$$n_p^e - n_p^* = \frac{\left(a_p - a_o\right) c}{\left(b_p - b_o + c\right)\left(b_p - b_o + 2c\right)} > 0,$$

which proves the second inequality. Then,

$$n_t^* - n_p^e = \frac{a_o - d}{b_o + \gamma} - \frac{a_p - a_o}{b_p - b_o + c} = \frac{\left(a_o - d\right)\left(b_p - \underline{b}_p\right)}{\left(\gamma + b_o\right)\left(b_p - b_o + c\right)} > 0,$$

which proves the third inequality. Furthermore,

$$n_t^e - n_t^* = \gamma \frac{a_o - d}{b_o \left(\gamma + b_o\right)} > 0,$$

proving the fourth inequality. Finally,

$$N - n_t^e = \frac{a_o}{b_o} - \frac{a_o - d}{b_o + \gamma} = \frac{d b_o + \gamma a_o}{b_o \left(\gamma + b_o\right)} > 0,$$

which proves the fifth inequality. ■

Appendix D. Proofs of propositions and corollaries

D.1. Proof of Corollary 1

After substituting the values of $\widetilde{n}$ from (13) and $\widehat{n}$ from (17) and simplifying, the condition $\widetilde{n} > \widehat{n} - n^*$ becomes

$$\lambda t^* = \frac{\lambda (c + \gamma)}{b + 2c + \gamma} (a - d) < a,$$

which always holds as $\frac{\lambda(c+\gamma)}{b+2c+\gamma} < 1$. ■

D.2. Proof of Proposition 2

▶ *Expected gains associated to tolls* . After substituting t^* from (8), expression (20) can be rewritten as

$$-\frac{n^*}{n^e} \left[(c + \gamma) n^* - c \left(n^e - n^*\right)\right] - b\frac{(n^e - n^*)^2}{2n^e} + \lambda \frac{(c + \gamma) (n^*)^2}{N} + \gamma \frac{(n^e)^2 - (n^*)^2}{2N}. \tag{D.1}$$

Finally, evaluating this expression at $\lambda = 1$ (i.e., its maximum with respect to λ), using (6), (7), and $N = a/b$, we obtain

$$-\frac{b}{2} (c + \gamma) (a - d) \frac{ac (b + c) + \left(b^2 + 2c^2 + c\gamma + 2bc\right) d + (b + 2c + \gamma) d \left(b - \underline{b}\right)}{a (b + c)^2 (b + 2c + \gamma)^2} < 0,$$

meaning that (D.1) is negative for all λ.

▶ *Expected gains associated to LEZ*. Expression (21) can be rewritten as

$$\frac{n^e - n^*}{n^e} \left(n^* c - b\frac{n^e - n^*}{2}\right) + \gamma \frac{(n^e)^2 - (n^*)^2}{2N}.$$

Making use of (6), (7), $N = a/b$, and $d < a/2$, this expression becomes

$$\frac{(a - d) (c + \gamma) \left\{ac (b + c) (b + 2c) + [(a - 2d) b + (2a - 3d) c] b\gamma + (a - d) b\gamma^2\right\}}{2a (b + c)^2 (b + 2c + \gamma)^2} > 0. \quad ■$$

D.3. Proof of Proposition 3

Claim 7. *There exits a unique $\widetilde{\gamma}$ such that $T/N < t_o^*$ for $\gamma > \widetilde{\gamma}$ and $T/N > t_o^*$ for $\gamma < \widetilde{\gamma}$.*

Proof. Using (33) and (34), then

$$T/N - t_o^* = \frac{(c + \gamma) (n_p^*)^2 - \gamma n_t^* \left(N + n_p^* - n_t^*\right)}{N}. \tag{D.2}$$

First, notice that (D.2) is positive for γ arbitrarily small (i.e., $\gamma \to 0$)

$$\lim_{\gamma \to 0} \left(T/N - t_o^*\right) = \frac{c(n_p^*)^2}{N} > 0$$

and negative for γ arbitrarily large (i.e., $\gamma \to \infty$)

$$\begin{aligned}
\lim_{\gamma \to \infty} \left(T/N - t_o^*\right) &< \lim_{\gamma \to \infty} \frac{c(n_p^*)^2 - \gamma n_t^* \left(N - n_t^*\right)}{N} \\
&= \lim_{\gamma \to \infty} \frac{c \left(\frac{a_p - a_o}{b_p - b_o + 2c}\right)^2 - \gamma \frac{a_o - d}{b_o + \gamma} \left(N - \frac{a_o - d}{b_o + \gamma}\right)}{N} \\
&< \lim_{\gamma \to \infty} \frac{c \left(\frac{a_p - a_o}{\underline{b}_p - b_o + 2c}\right)^2 - \gamma \frac{a_o - d}{b_o + \gamma} \left(N - \frac{a_o - d}{b_o + \gamma}\right)}{N} \\
&= \lim_{\gamma \to \infty} \frac{c \left(\frac{(a_p - a_o)(a_o - d)}{c(a_o - d) + (a_p - a_o)(\gamma + b_o)}\right)^2 - \gamma \frac{a_o - d}{b_o + \gamma} \left(N - \frac{a_o - d}{b_o + \gamma}\right)}{N}
\end{aligned}$$

$$= -\left(a_o - d\right) < 0 \text{ (applying L'Hôpital's rule),}$$

where $\gamma (n_p^*)^2 - \gamma n_t^* n_p^* < 0$ is used to derive the first inequality; and $b > \underline{b}_p = \left(b_o + \gamma\right) \frac{(a_p - d)}{(a_o - d)} - (\gamma + c)$ is used to derive the second inequality.

Second, using $\frac{\partial n_t^*}{\partial \gamma} = -\frac{n_t^*}{b_o + \gamma}$, it can be shown that (D.2) is decreasing in γ, i.e.,

$$\begin{aligned}
\frac{\partial\left(T/N - t_o^*\right)}{\partial \gamma} &= \frac{(n_p^*)^2 - n_t^*\left(N + n_p^* - n_t^*\right) - \gamma \frac{\partial n_t^*}{\partial \gamma}\left[\left(N + n_p^*\right) - 2\left(n_t^*\right)\right]}{N} \\
&= \frac{(n_p^*)^2 - \frac{\gamma}{b_o + \gamma}\left(n_t^*\right)^2 - \frac{b_o}{\gamma + b_o} n_p^* n_t^* - \frac{b_o}{\gamma + b_o}\left(N - n_t^*\right) n_t^*}{N} \\
&< \frac{(n_p^*)^2 - \frac{\gamma}{b_o + \gamma}\left(n_p^*\right)^2 - \frac{b_o}{\gamma + b_o}\left(n_p^*\right)^2 - \frac{b_o}{\gamma + b_o}\left(N - n_t^*\right) n_t^*}{N} \\
&= -\frac{b_o\left(N - n_t^*\right) n_t^*}{\left(\gamma + b_o\right) N} < 0,
\end{aligned}$$

where $n_t^* > n_p^*$ is used to derive the above inequality. ■

Claim 8. $T/N < t_p^*$.

Proof. Using (32) and (34), then

$$T/N - t_p^* = \frac{-(c + \gamma) n_p^*\left(N - n_p^*\right) + \gamma n_t^*\left(n_t^* - n_p^*\right)}{N}.$$

Noticing that

$$-(c + \gamma) n_p^* + \gamma n_t^* = -\frac{\gamma\left(a_o - d\right)\left(\bar{b}_p - b_p\right)}{\left(\gamma + b_o\right)\left(b_p - b_o + 2c\right)} < 0,$$

is a sufficient condition for $T/N - t_p^* < 0$ as $n_t^* < N$, the statement included in the claim is proven. ■

D.4. Proof of Corollary 4

Proposition 3 (along with Fig. 3) shows three considered alternatives ($tolls$, LEZ, and $comb$) and three population groups ($i \in \left[0, n_p^*\right]$, $i \in (n_p^*, n_t^*]$, and $i \in (n_t^*, N]$). Under $\gamma > \tilde{\gamma}$, each of these alternatives is ranked first, second, and third in one of these groups. Hence, if neither of these groups has a majority, i.e., having a size larger than $N/2$, a voting cycle emerges. This occurs when $max\left\{n_p^*, n_t^* - n_p^*\right\} < N/2 < n_t^*$. ■

Appendix E. Ordering of n_u^*, $\hat{n}_u$, n_u^e (urban) and n_s^{toll}, n_s^*, $\tilde{n}_s$, $\hat{n}_s$, n_s^e (suburban)

Claim 9. *The following ordering can be established:* $0 < n_u^* < \hat{n}_u < n_u^e < N_u$.

Proof. First, notice that $n_u^* < \hat{n}_u$ requires

$$\hat{n}_u - n_u^* = n_u^e - n_u^* - \frac{1}{b_u} \sigma_u \gamma \frac{\left(n_t^e\right)^2 - \left(n_t^*\right)^2}{2N_u} > 0,$$

which is always guaranteed by imposing a lower bound for b_u in the same fashion as in the baseline model (see Appendix B). Second, $\hat{n}_u < n_u^e$ follows immediately from inspection of ((48)). Finally, $0 < n_u^*$ and $n_u^e < N_u$ are always observed. ■

Claim 10. *The following ordering can be established:* $0 < n_s^{toll} < n_s^* < \tilde{n}_s < \hat{n}_s < n_s^e < N_s$.

Proof. First, notice that $n_s^{toll} < n_s^*$ because

$$n_s^{toll} - n_s^* = n_t^* - n_u^e - n_s^* = -\frac{b_s (c + \gamma)}{b_s b_u + c\left(b_s + b_u\right)} n_t^* < 0.$$

Second, $n_s^* < \tilde{n}_s$ requires

$$\tilde{n}_s - n_s^* = n_s^e - n_s^* - \frac{1}{b_s}\left(\frac{t^* n_s^{toll}}{N} + \sigma_s \gamma \frac{\left(n_t^e\right)^2 - \left(n_t^*\right)^2}{2N_s}\right) > 0,$$

which is always guaranteed by imposing a lower bound for b_s in the same fashion as in the baseline model (see Appendix B). Third, $\widetilde{n}_s < \widehat{n}_s < n_s^e$ follows immediately from inspection of (49) and (50). Finally, $0 < n_s^t$ and $n_s^e < N_s$ are always observed. ■

Appendix F. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2022.102719.

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