The Political Economy of Cordon Tolls

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Abstract

This paper studies the political economy of cordon tolls in a monocentric city consisting of three zones: center, mid-city and suburbs. The cordon toll may give rise to several interrelated conflicts: between residents within and outside the cordon, between car and public transport users, between the rich and the poor and, as the toll capitalizes into rents, between landowners and renters. These conflicts drive all our results. In the short-run, we assume the population is immobile and rents are fixed. With identical individuals, the toll then increases commuting costs only for those outside the cordon. Unless residents within the cordon are the majority, the equilibrium toll resulting from the political process is below the optimal level. Allowing for heterogeneous values of time, rich car commuters prefer a toll higher than socially optimal but, unless access costs to public transit are small, the poor majority prefers a toll below the optimum. When the toll capitalizes into land rents within the cordon, we show that only voters owning land in the center support it. In all scenarios, earmarking revenues for public transport mitigates the effect of the toll on commuting costs, raising voter support. Finally, we find that it is easier to get support for a cordon close to the center than for one further out in the suburbs. We illustrate our results using a calibrated model based on data for Milan.

JEL-Code: R410, D780, H230.

Keywords: cordon tolls, voting, land market, transit subsidies, Milan.

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1. Introduction

Economists have long advocated road pricing to reduce the external costs generated by automobile traffic. Ideally, first-best pricing requires sophisticated, distance-based instruments that allow charging users in function of congestion and pollution levels. Unfortunately, in urban areas such instruments are difficult to implement, as one would have to monitor each car's path to compute the relevant charges. City governments have therefore focused on less ambitious but feasible second-best policies: almost all urban road pricing schemes that currently exist (or have recently been contemplated) are *cordon tolls*. The idea, implemented in London, Milan, Singapore and Stockholm among other cities, is to place a 'cordon' around the city center and charge drivers entering the area so defined.

Although the issue is on the political agenda in many cities, governments often appear unable or unwilling to implement cordon pricing. The list of examples where tolls have been discussed, but not adopted, is much longer than the few examples of successful introduction given before; it includes New York, San Francisco, Birmingham, Edinburgh, Manchester, Paris, several cities in Belgium and the Netherlands, etc. Political acceptability of road pricing seems still a major challenge (Small and Verhoef (2007)). To better understand why this is the case, this paper develops a simple political economy model of cordon pricing. Intuitively, imposing a cordon toll gives rise to several potential conflicts between inhabitants: between residents within and outside the cordon, between car and public transport users, between the poor and the rich and, when the toll capitalizes into rents, between landowners and renters. These potential conflicts drive our results. A numerical application based on data for Milan, Italy, illustrates our findings.

Following Brueckner and Helsley (2011) and Brueckner (2015), we model a monocentric city consisting of three zones: the center, where all employment is located, a midtown and a suburban zone. Residents commute daily to the center, either by car or public transit. The road system is congestible and transit suffers from peak-hour crowding. We model the cordon toll as a tax on all cars entering the central zone and consider various ways to recycle the toll revenues, including lump-sum redistribution and earmarking to subsidize public transport. The toll is decided by majority voting.

The analysis proceeds in several steps. First, the baseline model considers a short-run scenario where populations in the various zones are immobile, so that the toll has no impact on the land market. Individuals are identical. Unless the toll is used to a large extent to subsidize public transport, it increases the cost of commuting for all those outside the cordon: car users pay more than the value of the reduction in congestion, public transport users face increased crowding. Residents within the cordon benefit. As a result, unless residents inside the cordon are the majority of the population, voting results in a toll below the socially optimal level (or even no toll). The government can mitigate the increase in commuting costs -- and thus buy support for the toll -- by using it to finance public transport subsidies. Specifically, the difference between the socially optimal toll and the equilibrium one is smaller the higher the subsidy.

Second, we introduce differences in value of time between poor and rich commuters. We let the rich commute by car, whereas the poor either drive or use public transport. This choice depends on user costs, including an idiosyncratic cost of accessing the transit network. We show that the rich prefer a toll higher than socially optimal, because they gain from lower congestion. However, poor car commuters suffer. The higher the user cost of public transport, the larger the share of poor individuals who drive and, thus, the larger the fraction of people that prefers a toll lower than the socially optimal level. When this fraction is large enough, the voting equilibrium entails a toll below the optimum. As in the baseline model, earmarking toll revenues for public transit improves acceptability.

Third, we reconsider the baseline model when urban residents are mobile. To avoid the toll, individuals can now move to the area enclosed in the cordon. The toll then capitalizes into central land prices, redistributing wealth in favor of those who own land there. Hence, regardless of where they live, voters generally fail to internalize the social benefits of the toll, except if they own a substantial lot of land inside the cordon. Only voters who own much land in the central zone will support the socially optimal toll. However, by attenuating the increase in commuting costs, higher transit subsidies mitigate the increase in land rent. They weaken the redistributive effects that work through the land market and, thus, voters' opposition to the toll.

Finally, the conflict between residents within and outside the cordon suggests that the location of the toll may be important for the political outcomes. The question then arises whether it is easier to get voters to favor a toll close to the center or one further out towards the suburbs. Although theoretical arguments do not provide an unambiguous answer, numerical analysis calibrated for Milan data indicates that voters are more likely to support a small cordon. Intuitively, this toll generates more revenues than one further out, and it is more effective at reducing congestion. Hence, both central residents (who do not pay the toll, independently of where it is located) and suburban residents (who pay in any case) prefer a smaller cordon area.

Our findings are consistent with several stylized facts. First, tolls generally find low political support. This is what the model would suggest, as both the small area of real-world cordons and the scarcity of land within the cordon make it highly unlikely that the majority of voters resides or owns land there. Second, support is typically much lower among non-central than among central city residents.[1] Third, our findings are in line with city governments tying tolls to public transport to increase acceptability. Finally, cordons are typically limited to a small area close to the center.

This paper belongs to a small but growing literature on the political economy of transport policy. Few papers in this literature model space and the land market.[2] Brueckner and Selod (2006) focus on the trade-off between monetary and time costs in choosing the city's transport system. In a model with rich and poor individuals, Borck and Wrede (2005, 2008) describe conditions under which voters support a commuting subsidy. Our paper differs by incorporating road congestion. Furthermore, it distinguishes between the short- and the long-run. In addition, whereas Borck and Wrede's focus is on kilometer charges, we study a cordon toll. The discontinuous nature of this tax leads to remarkably different implications.

Our analysis also contributes to the literature on cordon tolling. Mun et al. (2003) studied a monocentric city with no land market. They show that an optimally located toll yields almost as much benefit as the first-best Pigouvian toll. Mun et al. (2005) extend the analysis to a polycentric city. Verhoef (2005) allows for endogenous rents, residential densities and labor supply, but still finds cordon tolls to be close to first-best. More recently, Tikoudis et al. (2015) extended the model further to consider different toll rebate rules. Brueckner (2015) emphasizes that a cordon toll has an effect on land rents that is non-monotonic in distance from the city center. He shows that the absence of pricing on suburban roads implies that the second-best toll is higher than the first-best one.[3] Takayama and Kuwahara (2017) analyze bottleneck congestion in a monocentric city, showing that, depending on the distribution of schedule-delay costs, a time-varying toll may lead the city to expand outwards.

A brief overview of the paper follows. We introduce the model in Section 2. In Section 3 we analyze voting behavior by residents in a short-run setting when households are immobile so that rents are fixed. We first present a baseline model assuming identical households (section 3.1), next we extend the model to allow for heterogeneity in the value of time between the rich

[1] The case of Stockholm provides one example: the majority of residents within the Municipality voted in favor of the toll, whereas outside residents voted against (Winslott-Hiselius *et al.*, 2008, fig. 6 and 7).

[2] See, e.g., De Borger and Proost (2012) and Russo (2013) for political economy studies ignoring the land market. Bento, Franco and Kaffine (2006) study anti-sprawl policies distinguishing landowners according to where they own land, though not in a political economy framework.

[3] A number of papers have developed large-scale numerical models to study the implications of cordon tolling. These include Safirova et al. (2006), De Lara et al. (2013), and Anas and Hiramatsu (2013) focusing on Washington D.C., Paris and Chicago, respectively. A few papers evaluate real-world cordon tolling experiences (e.g., Santos (2008), Eliasson (2008) and Rotaris et al. (2010)).

and the poor (section 3.2). Section 4 introduces household mobility into the baseline model, so that the cordon toll will capitalize into higher rents within the cordon. Section 5 gives some insight into the political economy of toll location. A numerical application for Milan is developed in Section 6. The conclusion follows in Section 7.

2. The model

We adopt the spatial structure proposed by Brueckner (2015). We consider an urban area consisting of three 'islands' or zones: a central zone *C* where the employment center (CBD) is located, a midtown zone *M* and a suburban zone *S*, which includes the urban area's boundary.[4] See Figure 2. We normalize the size of *C* to one, and let the size of *M* be $Q_M \geq 1$. The suburban zone *S* is "large", in the sense that there is a perfectly elastic supply of land there, at a constant rental price denoted r_s.

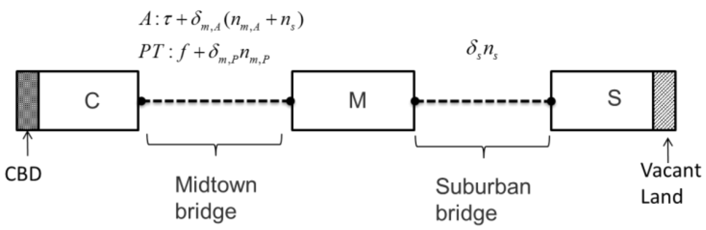

Figure 1: Spatial setup and commuting costs

The total population of the urban area is exogenous and denoted by *N*, where

$$N = n_c + n_m + n_s. \tag{1}$$

In this expression, n_c, n_m, n_s refer to the number of individuals that live in zones *C*, *M* and *S*, respectively. We assume that residential lot sizes in each zone q_j $(j = c, m, s)$ are exogenous. In accordance with real-world observation, we assume that $q_c < q_m < q_s$.

Commuting. All individuals commute to the CBD. To simplify the analytics, we assume the following. First, we normalize the cost of traveling to the CBD to zero for inhabitants of zone *C*. Second, we assume that commuters living in *S* all travel to the CBD by car. This assumption could capture low density of public transport networks in the suburbs, resulting in the absence of convenient alternatives to cars. Alternatively, it may reflect a steeply rising cost of using the

[4] Some of our results can be derived having only two zones, but for other sections having three zones is essential (most obviously for analyzing toll location).

public transit system as one moves away from the center.[5] Third, the public transport system between the midtown zone *M* and the CBD is well developed, so that residents of *M* can commute by car or public transport.[6] In the baseline model, we treat these two modes as perfect substitutes from the viewpoint of commuters from zone *M*, see below. We denote the number of midtown residents traveling by car and public transport by $n_{m,A}$ and $n_{m,P}$, respectively. Of course, we have

$$n_m = n_{m,A} + n_{m,P}\,. \tag{2}$$

We model the cost of commuting by car between the different zones by assuming that a midtown bridge connects *C* to *M*, whereas a suburban bridge connects *M* to *S*. To capture congestion, we specify the costs of crossing the respective bridges -- capturing both money and time costs but excluding possible toll payments -- as a linear function of the number of automobile commuters:

$$\delta_{m,A}(n_{m,A} + n_s) \quad \text{and} \quad \delta_s n_s\,, \quad \text{with } \delta_{m,A} > 0, \delta_s > 0\,. \tag{3}$$

Linearity simplifies the analytics, but is not crucial for the results.[7] Note that we normalized the free-flow generalized cost to zero without loss of generality.

Following a simple but ingenious suggestion of Brueckner (2015), we implement the idea of a cordon toll by assuming that auto commuters have to pay a tax τ on the midtown bridge, whereas there is no tax on the suburban bridge. Hence, all car traffic entering the central zone pays τ.

Turning to public transport, the generalized cost of a trip from *M* to the CBD is

$$f + \delta_{m,P} n_{m,P}, \quad \text{with} \quad \delta_{m,P} > 0. \tag{4}$$

In this expression, f is the public transport fare. The second term specifies the generalized cost as an increasing function of the number of users: this captures both the increase in the user's time cost and the extra disutility due to crowding.[8] For simplicity, we specify this relation linearly. As for road congestion, we ignore the time cost at zero demand. Moreover, we assume public transport does not interact with car traffic. We discuss these assumptions at the end of this subsection.

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[5] See LeRoy and Sonstelie (1983), Sasaki (1990) and Borck and Wrede (2008) for models incorporating similar assumptions.

[6] We limit modal choice decisions to residents of zone *M*. Modeling modal choices for residents of all zones, together with assuming a Wardrop user equilibrium (see below), substantially complicates the analysis without offering extra insights.

[7] A linear congestion function is consistent with structural models of congestion, such as the bottleneck model (Arnott, de Plama and Lindsey (1993)).

[8] The relevance of peak-hour crowding in public transport is well documented (Tirachini, Hensher and Rose (2013); Haywood and Koning (2015)).

We want to avoid that political decisions involve voting on the toll and the public transport fare jointly, because multi-dimensional majority voting generally implies the absence of an equilibrium (Persson and Tabellini, 2000). Therefore, we make two further assumptions, specifically related to pricing of public transport trips. First, in the absence of subsidies, the public transport agency prices at marginal social cost; in other words, the agency takes into account crowding externalities on public transport when setting the public transport fare. This is a heroic assumption, but it helps to keep the focus on the political economy of cordon pricing. By avoiding an extra distortion due to suboptimal pricing of public transport services, it simplifies the analytics without affecting the main results, see below. Second, we allow the government to use some of the toll revenues to subsidize the user cost of public transport. In line with these assumptions, we specify the public transport fare *f* as:

$$f = \delta_{m,P} n_{m,P} - \sigma. \tag{5}$$

The first term captures the external crowding cost of a public transport trip, which increases in the number of public transport users. The second term σ is the direct subsidy per trip. To keep the model as simple as possible, we capture the link between the toll and transit subsidies as follows:

$$\sigma = \alpha\tau, \qquad \alpha \geq 0. \tag{6}$$

If $\alpha = 0$, the toll has no effect on the public transport fare. By contrast, when $\alpha > 0$ the toll induces the government to provide an extra subsidy to public transport; the remaining toll revenue is lump-sum reimbursed to consumers.[9] This formulation therefore allows for lump-sum redistribution of all toll revenue, as well as for earmarking (part of) this revenue for transit subsidies.[10] Combining (4), (5) and (6), the generalized cost of a public transport trip can be written as:

$$2\delta_{m,P} n_{m,P} - \alpha\tau. \tag{7}$$

Preferences. We assume that individuals have an exogenous surplus *V* from residing in the city. Furthermore, they care for consumption of a composite good *e*, treated as the numeraire.

[9] The introduction of the toll is therefore budgetary neutral. Note that we do not impose a formal budget restriction on public transport operations.

[10] In practice, cities use toll revenues also to improve public transport service (frequency, extra lines, etc.). We could easily incorporate these effects in the model, but without adding much insight. Note also that we could assume "strict" earmarking, whereby total subsidies are a fraction of toll revenues (instead of tying the subsidy to the toll itself). This would also complicate matters but yield qualitatively similar insights. Observe that it is not obvious that strict earmarking is more realistic: it is well known that governments have some spending flexibility to partly circumvent earmarking rules (see e.g., Bös (2000, p.444)).

An individual's utility is thus given by $U = V + e$. Individuals spend time either working or commuting. We assume a fixed wage, normalized at one, and an exogenously given working time *Y*. Due to differences in commuting costs and in lot size, the budget and time constraints of an individual depend on where she lives. We combine these constraints to obtain the following, for people living in *C*, *M* (car users and public transport users) and *S*, respectively:

$$e_c + r_c q_c = Y + T + R, \qquad (C)$$

$$e_m + r_m q_m + \tau + \delta_{m,A}\left(n_s + n_{m,A}\right) = Y + T + R, \qquad (M\text{, car user})$$

$$e_m + r_m q_m + 2\delta_{m,P} n_{m,P} - \alpha\tau = Y + T + R, \qquad (M\text{, public transport user})$$

$$e_s + r_s q_s + \tau + \delta_{m,\mathrm{A}}\left(n_s + n_{m,A}\right) + \delta_s n_s = Y + T + R. \qquad (S)$$

The left-hand side of these expressions, which depends on residential location, captures expenditures; r_j and q_j are the rental prices of land and lot size in zone $j = c, m, s$. If the individual lives in zone *C*, her commuting cost is zero, but she pays r_c per unit of land. An individual living in *M* pays r_m per unit of land, but faces commuting costs of $\tau + \delta_{m,\mathrm{A}}\left(n_s + n_{m,A}\right)$ or $2\delta_{m,\mathrm{P}} n_{m,P} - \alpha\tau$ when traveling by car or public transport, respectively. Finally, an individual living in *S* has to sustain the additional commuting cost $\delta_s n_s$, but pays only r_s per unit of land.

The right-hand side of the budget constraints above capture the individual's income. This consists of three elements. First, labor income *Y*, which is the same for all urban residents. Second, the government redistributes the net toll revenue (that is, net of public transport subsidies) in the form of a lump-sum transfer *T*. Specifically, we have

$$T = \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,\mathrm{P}} n^2{}_{m,P}}{N}. \qquad (8)$$

Finally, *R* is individual income generated out of landownership. This term only plays a role when the toll affects rents, see Section 4.

3. The political economy of cordon tolling: the short run

To set the stage, we consider a short-run setting in which an individual's location within the city is exogenous. This assumption captures the fact that relocation costs are significant in the short term. As a consequence, the toll has no effect on the city's land market: resident populations n_j and the rental prices of land r_j are given; the toll only affects commuters' mode choice and their welfare via two main channels, viz. changes in commuting costs and in redistributed net toll revenues.

We begin by analyzing the baseline model, assuming that individuals are identical (Section 3.1). We then extend the analysis (Section 3.2) to allow for heterogeneity in time values and in the costs of accessing the transit system.

3.1. The baseline model

The purpose of this section is to emphasize the role of congestion, of crowding in public transport, and of earmarking the toll revenues for the voting equilibrium that is likely to result. As mentioned above, we treat car and public transport as perfect substitutes from the perspective of commuters in *M*. We can therefore invoke the Wardrop user equilibrium condition, implying (assuming both modes are used) equality of the generalized costs (*GC*) of traveling from *M* to the CBD by car and public transport:

$$GC = \tau + \delta_{m,A}\left(n_s + n_{m,A}\right) = 2\delta_{m,P}n_{m,P} - \alpha\tau. \tag{9}$$

Using (9) we determine the effect of the toll on the number of car and public transport commuters from *M* to *C*. We find:

$$\frac{dn_{m,A}}{d\tau} = -\frac{dn_{m,P}}{d\tau} = -\frac{1+\alpha}{\delta_{m,\mathrm{A}} + 2\delta_{m,P}} < 0. \tag{10}$$

The toll reduces car use and raises public transport use. These effects are less pronounced when the midtown road is highly congestible and there is much crowding in public transport. Moreover, as expected, the effect of the toll is stronger when more revenue is used to subsidize public transport, i.e., the larger is α .

For later reference, note that the Wardrop equilibrium has an interesting implication. Differentiating the left-hand and right-hand sides of (9) with respect to the toll and using (10), we obtain the following effects on the generalized cost of car and public transport use:

$$\frac{dGC}{d\tau} = 1 + \delta_{m,\mathrm{A}}\frac{dn_{m,A}}{d\tau} = -2\delta_{m,\mathrm{P}}\frac{dn_{m,A}}{d\tau} - \alpha = \frac{2\delta_{m,\mathrm{P}} - \alpha\delta_{m,\mathrm{A}}}{\delta_{m,\mathrm{A}} + 2\delta_{m,\mathrm{P}}}. \tag{11}$$

This expression shows that a marginal increase in the toll may increase or decrease the generalized cost of commuting for both modes. For example, if the government does not use any of the revenue to subsidize public transit (i.e., $\alpha = 0$), the higher toll makes some car commuters switch mode, raising crowding and hence the user cost of transit. In equilibrium, all commuters face higher generalized costs. This outcome is what one would expect; it is consistent with the findings of numerical simulation models of cordon tolls (see, e.g., Mun et al. (2003), Anas and Hiramatsu (2013)). However, when the toll revenue is used to a large extent for subsidizing public transport, in principle the opposite may hold. If $2\delta_{m,\mathrm{P}} < \alpha\delta_{m,\mathrm{A}}$, the subsidy tied to the toll is so large that a higher toll yields a decline in equilibrium commuting costs. The modal shift to transit is so large that the reduced congestion levels more than outweigh the toll increase.

The social optimum

We first characterize the socially optimal toll, i.e., the toll that maximizes the total utility of the urban population. The Wardrop condition (9) implies that, in equilibrium, the utility of residents of zone *M* is independent of whether they use car or public transport. The optimal toll thus solves the following problem:[11]

$$\underset{\tau}{Max} \quad W = n_c U_c + n_m U_{m,A} + n_s U_s, \tag{12}$$

Using earlier specifications, we can write the utilities in (12) as follows:

$$U_c = V - r_c q_c + Y + R + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,\mathrm{P}} n^2_{m,P}}{N}, \tag{13}$$

$$U_{m,A} = V - r_m q_m - \tau - \delta_{m,\mathrm{A}}\left(n_s + n_{m,A}\right) + Y + R + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,\mathrm{P}} n^2_{m,P}}{N}, \tag{14}$$

$$U_s = V - r_s q_s - \tau - \delta_{m,A}\left(n_s + n_{m,A}\right) - \delta_s n_s + Y + R + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,P} n^2_{m,P}}{N}. \tag{15}$$

Substituting these expressions in (12), differentiating and using (11), we easily find the optimal short-run toll τ^{SR} (recall that r_j, n_j and q_j are exogenous):

$$\tau^{SR} = \frac{\delta_{m,A}\left(n_s + n_{m,A}\right)}{1+\alpha}. \tag{16}$$

With lump sum redistribution (i.e., $\alpha = 0$), τ^{SR} equals the marginal external cost of car use. This is as expected, given that the public transport fare corrects for the external cost of

[11] Note that we characterize a constrained optimum, in the sense that we assume a positive number of users on both modes in the optimal allocation. To streamline the exposition, we ignore possible corner solutions where all commuters use the same mode.

crowding; moreover, congestion on the suburban bridge is unaffected by the toll, because the number of commuters from *S* to the *CBD* is exogenous in the short run, and they all commute by car. In the case of earmarking ($\alpha > 0$), the optimal toll decreases. The intuition is that the toll and the subsidy have a symmetric effect: they both make commuting by car relatively more expensive.

Interestingly, the model implies that when the government adopts the optimal toll, the modal choice of commuters is independent of α . To see this, substitute (16) into (9) and solve for $n_{m,A}$ to find:

$$n_{m,A}\Big|_{\tau=\tau^{SR}} = \frac{\delta_{m,P} n_m - \delta_{m,A} n_s}{\delta_{m,A} + \delta_{m,P}}. \tag{17}$$

Since modal choice is the only endogenous choice margin for city residents in the short run, this finding has an important consequence. It implies that if the toll is optimal ((16) holds), social welfare is maximal regardless of how the government uses the toll revenues. The government can therefore link the optimal toll to higher transit subsidies -- in an attempt to influence the political equilibrium -- without affecting the social optimum, i.e., without introducing distortions. This observation will be useful for the interpretation below.

The political equilibrium

The first step is to determine the tolls preferred by residents of each zone; we denote these tolls by τ^i, $i = C, M, S$. Consider residents of zone *C*. Their preferred toll τ^C maximizes (13). We obtain:

$$\tau^C = \frac{1}{1+\alpha}\left(\delta_{m,A}\left(n_s + n_{m,A}\right) + \frac{\left(2\delta_{m,P} - \alpha\delta_{m,A}\right)\left(n_m + n_s\right)}{1+\alpha}\right). \tag{18}$$

This toll deviates from (16) because of the last term between the brackets. First assume toll revenues are redistributed lump-sum ($\alpha = 0$). Comparing (18) and (16) then immediately implies that residents of *C* prefer a toll larger than the socially optimal toll.[12] The intuition is easy. Given lump-sum redistribution we know (see (11)) that a higher toll raises commuting costs by either mode for people from *M* and *S*. However, residents of *C* do not incur any

[12] One should be cautious when making this comparison, because the toll expressions are not closed-form solutions. However, it is easily shown that they do imply $\tau^C > \tau^{SB}$. To do so, solve (9) for $n_{m,A}$, substitute the tolls into this expression, and substitute the result back into the toll formulas to get an explicit solution for the tolls. The comparison then immediately follows.

commuting cost; they are only interested in the redistributed toll revenues. They therefore ignore the burden that the toll imposes on the rest of the population. Of course, the social optimum does take into account the effect of the toll on the well-being of commuters from *M* and *S*. As a consequence, people in the center *C* prefer a toll above socially optimal. Second, note that using some of the toll revenues for transit subsidies ($\alpha > 0$) reduces the last term between brackets, because subsidies mitigate the increase in commuting costs. Furthermore, there is less net revenue to be redistributed. Hence, the preference of central residents for an exceedingly high toll is reduced. In fact, (18) suggests that when earmarking is very strong, the last term in brackets becomes negative, so central residents may in principle want a toll below the optimal one.

Consider the preferences of residents in *M* and *S*. Their preferred tolls τ^M and τ^S maximize (14) and (15). Given our assumptions, the toll has no effect on traffic on the suburban bridge so that the effect of the toll on suburban and midtown residents is identical. Maximizing (14) and (15), we find:

$$\tau^M = \tau^S = \frac{1}{1+\alpha}\left(\delta_{m,A}\left(n_s + n_{m,A}\right) - \frac{\left(2\delta_{m,P} - \alpha\delta_{m,A}\right)n_c}{1+\alpha} \right). \tag{19}$$

This rule has the same structure as (18), but the last term has the opposite sign. The reason is that, unlike residents in *C*, residents in *M* and *S* see their commuting costs change with the toll. If these costs increase, midtown and suburban residents fail to fully internalize the social benefits of tolling. As a result, they want a toll below the social optimum (and possibly even no toll). However, earmarking revenues for transit attenuates the increase in commuting costs and therefore reduces opposition to the toll; technically, it reduces the magnitude of the last term in (19).[13]

What toll level will result from the political process? To answer this question, we assume that the government chooses the toll via a majority voting procedure. Consider first the case where the government redistributes toll revenues entirely in lump-sum fashion, i.e. $\alpha = 0$. Comparing (16) - (19), using the procedure explained above (see footnote 10) it follows that:

$$\tau^C > \tau^{SR} > \tau^M = \tau^S. \tag{20}$$

[13] If $2\delta_{m,P} < \alpha\delta_{m,A}$, non-central commuters actually prefer a toll above the socially optimal level; the intuition is that large enough subsidies drive equilibrium commuting costs down, despite the toll (see (11)).

In this simple setting, it is straightforward to show that the majority voting equilibrium coincides with the preferred toll of the median individual. Obviously, if one group accounts for more than half the total population, the median voter belongs to this group. Otherwise, (20) indicates that the median voter is either a midtown or a suburban resident, so that the equilibrium toll is lower than the socially optimal one. The same qualitative outcome is obtained when the government partly uses the toll revenue to subsidize transit, as long as the toll increases the generalized cost of commuting in equilibrium, i.e. $2\delta_{m,P} - \alpha\delta_{m,A} > 0$. However, earmarking does reduce the difference between the socially optimal and the equilibrium toll (recall that the size of the last term in (19) decreases with α). In fact, expressions (16)-(19) indicate that

$$\alpha = \frac{2\delta_{m,P}}{\delta_{m,A}} \Rightarrow \tau^M = \tau^S = \tau^C = \tau^{SR}. \qquad (21)$$

This suggests that the government can make the socially optimal toll acceptable to all residents if it is willing to complement the toll with a large enough increase in public transit subsidies. Of course, in practice this may be just a theoretical possibility. Budgetary restraints may limit the use of revenues for public transport. For instance, part of the revenue may have to cover the operating costs of the tolling system. Moreover, public transport operators may be subject to a revenue requirement.[14] However, the analysis indicates that, even though the government may not be able to achieve the optimum in practice, it can manipulate the outcome by earmarking the revenues for public transport, thereby raising welfare.

PROPOSITION 1: Consider the short-run scenario, and assume that residents within the cordon are not the majority of the population. With lump-sum revenue redistribution, the voting equilibrium is such that the toll is below the socially optimal level. Using the toll to increase public transport subsidies reduces the gap between the equilibrium toll and the socially optimal one.

This proposition illustrates the conflict between residents inside and outside the cordon: the toll produces an increase in the generalized commuting cost for outsiders, so that it

[14] It would be fairly easy to capture these issues by introducing an exogenous revenue requirement for the government, implying an upper bound on α .

redistributes welfare from those outside to residents inside the cordon (who do not pay, but receive higher redistributed revenues). The proposition is consistent with the observation that city governments are often unable to muster enough political support for cordon tolls. Moreover, it is also consistent with the typical finding that central residents indeed tend to support tolls more than non-central residents do (see Eliasson (2008) for some evidence). Nevertheless, the proposition also suggests that outside residents can be “bought out” through transit subsidies, raising support for the toll. This may be one of the explanations why many cities (including London, Stockholm and Milan) have tied the introduction of road pricing to public transport (often by earmarking a share of the revenues).

Our analysis was based on some strong assumptions. Some of these will be relaxed below, but some others will not, and they deserve some discussion at this point. First, public transport firms do not generally price their services optimally. Instead, fares are often determined by some average cost recovery criterion, and they may be kept inefficiently low for distributive reasons. However, our qualitative results on the political equilibria obtained are not sensitive to alternative assumptions on public transport fares. For example, assuming an exogenously imposed fare (e.g., a fare determined by an autonomous public transport agency) yielded results that were qualitatively the same in all relevant respects.

Second, our specification of the public transport user cost – implying linear crowding costs -- is no more than a convenient simplification. As noted by De Palma, Kilani and Proost (2015, p. 3), the most realistic function for crowding costs is probably piecewise linear, and it has two clearly identifiable kinks where costs shift upward. The first jump reflects the cost increase when seating capacity is reached, the second kink occurs when buses are full and the user cost function becomes vertical. Unfortunately, this specification is not tractable in theoretical work. However, the linear approximation we use may not be unreasonable for two reasons. One reason is that if one adopts the piecewise linear specification described above, the impact of the toll on crowding may range from very small (if the transit system has much spare capacity) to very large (if the system operates close to full capacity in the peak period). Given that we are only interested in equilibrium effects, our linear formulation could capture both situations, with an appropriate choice of slope. A second reason is that recent crowding models, estimated for Paris, find that crowding functions are empirically well approximated by a linear specification (Haywood and Koning (2015)). Statistically, given the range of demand available in their data, the authors could not reject the hypothesis of linearity.[15]

Third, it is true that, in cities where separate bus lanes have not been introduced, assuming zero interaction between cars and buses is not realistic. Although adapting the model to allow such interaction is not straightforward (see Tirachini et al. (2014) for such a model), intuitively one expects this to have similar effects as reducing the importance of crowding (reducing α). When the toll makes people switch to public transport, the interaction between cars and buses implies that the user cost of public transport rises less than it would in the absence of such interaction, because the reduction in the number of cars implies that buses face less hindrance from cars. Including the interaction between cars and buses is therefore very unlikely to overturn our results that (i) without subsidies, user costs for transit users would go up, undermining acceptability and (ii) subsidies are important to achieve political acceptability. For example, Transport for London (2008, p. 85) suggests that the majority of revenues from the congestion charge were devoted to public transport, precisely to prevent the increase in public transport demand generating overcrowding. It seems unlikely that a significant net gain in user cost to bus users could have been achieved without the extra subsidies, despite the improvement in road congestion.

Finally, following a standard approach in political economy (Downs, 1957), we studied the preferences of different groups and assumed the toll adopted is the majority voting equilibrium. By definition, this toll wins a majority against any alternative in a pairwise contest. Furthermore, our analysis allows determining whether a majority would accept an arbitrary toll (socially optimal or otherwise). In this sense, our model is consistent with the existing referenda (see, e.g., the Stockholm referendum) where voting was on a particular toll level at a given location. However, there are of course other ways to organize referenda. For example, residents could jointly vote on toll level and cordon location. Unfortunately, multi-dimensional majority voting problems are generally hard to study because the conditions for equilibrium existence are highly restrictive (Persson and Tabellini, 2000).

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[15] Note that crowding may be less important in cities where the transit system is used by few people, as seems to be the case in some US cities. In these cities the cost of accessing and using the transit system may be so large for many users that almost everyone goes by car, regardless of the toll. In that case, the Wardrop equilibrium does not hold. In an earlier version of the model, we considered such a case. We found that the qualitative results were similar to those of the current paper, with equilibrium tolls that were often below the socially optimal level.

3.2. Introducing heterogeneity

The baseline model assumed all commuters have the same value of time; moreover, we implicitly assumed access costs to public transport were equal (and normalized at zero). Of course, commuters have different values of time, and those with high time values are more likely to benefit from congestion charges. In addition, access costs to public transport may differ between commuters, and individuals may have idiosyncratic preferences for car versus public transport use. In this subsection, we extend the model to capture these ideas.

To keep the analysis tractable and in order not to distract attention from the main issues studied here, we simplify the model in several other respects. First, to emphasize the key tensions that follow from assuming differences in values of time and in idiosyncratic preferences towards car use, we normalize the number of individuals residing in zones *C* and *S* to zero. The reason we can adopt this simplification without consequences for the results is that, as will become clear below, the crucial dimension determining policy preferences of voters is their modal choice. Specifically, residents of zone C (who do not commute by car) have essentially the same preferences towards a cordon toll as residents of *M* who commute by public transport. Similarly, residents of *S* (who all commute by car) have identical preferences with respect to cordon tolling as car users living in *M*. Therefore, explicitly taking into account the inhabitants of *C* and *S* would only make the notation heavier without any benefit in terms of extra insight. A second simplification in this subsection is that we ignore crowding in public transport. This saves on notation and it simplifies the analytical derivations. Relaxing this assumption has predictable implications; they are briefly considered at the end of the section.

Since we focus only on individuals in the midtown zone, in the following we drop the location indexes from population and cost variables. We assume the commuting population in the midtown zone *M* belongs to one of two subgroups, characterized by either a high or low value of time, denoted w_i, $i = L, H$, with $w_H > w_L$. For convenience, we will refer to individuals in group H as the "rich", and to group L as the "poor". We denote the number of individuals in each group by n_i. Given the above assumptions, we have $\sum n_i = N$, where the latter denotes total population in the urban area. We assume that the majority of the population is poor, i.e. $n_L > n_H$.

The generalized cost of commuting by car is

$$\tau + w_i \delta_A n_A, \tag{22}$$

In this expression τ is the road toll; the second term captures the time cost of commuting by car. It is given by the individual's value of time, multiplied by the travel time $\delta_A n_A$ which, as in our baseline model, is a linear function of the number of car commuters. The number of car commuters is defined below, see (28).

We assume that people with high time values, the rich, always commute by car. Modal choice for the poor depends on money and time costs of the two modes, as well as on an idiosyncratic cost of using public transport. This cost can be interpreted either as an access cost (for example, the cost of walking to the nearest bus/underground station) or as reflecting an individual's preference for commuting by car. We denote this cost by *c*, and assume that it is distributed uniformly on the $\left[0,\bar{c}\right]$ interval. We specify the generalized cost of commuting by public transport as follows

$$f-\alpha\tau+w_L\delta_P+c, \tag{23}$$

where f is the fare, $\alpha\tau$ is the subsidy to public transport which is tied to the toll (as in (6) above), and δ_P is the travel time cost of public transport use. Note that, unlike in the baseline model, we ignore crowding costs, to focus on the role of individual heterogeneity. Therefore, we assume the travel time cost is exogenous, and so is the optimal (pre-subsidy) fare.

The utilities of individuals belonging to each group are

$$U_H=V-\tau-w_H\delta_A n_A+T, \tag{24}$$

$$U_L^A=V-\tau-w_L\delta_A n_A+T, \tag{25}$$

$$U_L^P(c)=V-f+\alpha\tau-w_L\delta_P-c+T. \tag{26}$$

Expression (24) represents the utility of a rich individual, and (25)-(26) give the utility of a poor person commuting by car and public transport, respectively. The latter includes the idiosyncratic cost *c*. Note that we ignore housing costs, which are exogenous in the short run.

Let $\tilde{c}$ denote the idiosyncratic cost of public transport characterizing the poor individual who is indifferent between the two modes. Using (25) and (26) we have

$$\tilde{c}=\tau+w_L\delta_A\cdot n_A-f+\alpha\tau-w_L\delta_P \tag{27}$$

Given our assumptions, poor individuals for which $c\geq\tilde{c}$ commute by car, whereas the others use public transport. Hence, we have

$$n_A=n_H+n_L\left(1-\frac{\tilde{c}}{\bar{c}}\right),\qquad n_P=n_L\frac{\tilde{c}}{\bar{c}}. \tag{28}$$

Combining (27) and (28), we find the following closed-from expressions for $\tilde{c}$ and n_A, respectively

$$\tilde{c} = \frac{\bar{c}\left[\tau(1+\alpha) + w_L\delta_A \cdot (n_H + n_L) - f - w_L\delta_P\right]}{\bar{c} + \delta_A w_L n_L} \tag{29}$$

$$n_A = \frac{\bar{c}(n_H + n_L) - n_L\left(\tau(1+\alpha) - f - \delta_P w_L\right)}{\bar{c} + \delta_A w_L n_L} \tag{30}$$

Using this last expression, we determine the effect of the toll on the number of car users:

$$\frac{dn_A}{d\tau} = -\frac{n_L(1+\alpha)}{\bar{c} + \delta_A w_L n_L} < 0. \tag{31}$$

Unsurprisingly, it is negative. Both a higher α and a larger number of poor people strengthen the modal shift triggered by the toll.

Social welfare is given by

$$W = n_H U_H + n_L\left(1 - \frac{\tilde{c}}{\bar{c}}\right)U_L^A + n_L \int_0^{\tilde{c}} U_L^P(c)dc. \tag{32}$$

Maximizing this expression with respect to τ, using $T = \frac{\tau(n_A - \alpha n_P)}{N}$ and the above expressions, we find the following welfare-optimal toll:

$$\tau^O = \frac{n_H w_H \delta_A + n_L w_L \delta_A\left(1 - \frac{\tilde{c}}{\bar{c}}\right)}{1+\alpha}. \tag{33}$$

The numerator of this expression is the marginal external cost generated by an additional car commuter. Note that this cost takes into account the different values of time of groups *H* and *L*. The denominator captures the effect of the subsidy which is mechanically tied to the toll. By increasing the relative cost of using the car, it reduces the optimal toll.

Consider the tolls preferred by each group, starting with the rich. Maximizing (24), we find

$$\tau_H = \frac{n_H w_H \delta_A + n_L w_L \delta_A\left(1 - \frac{\tilde{c}}{\bar{c}}\right) + \delta_A(w_H - w_L)n_L - \frac{\bar{c}n_P}{n_L}}{1+\alpha}. \tag{34}$$

The first two terms on the right hand side are identical to the welfare optimal toll in (33). The third terms captures the fact that the rich benefit from reduced congestion more than the poor. The last term reflects the idea that the toll has a negative effect on the budget of car commuters, because they receive a transfer from the government which is smaller than what they pay (revenues being redistributed also to public transport users). Thus, whereas the third term induces the rich to prefer a higher toll than optimal, the fourth term implies the opposite.

The poor partly go by car, partly by public transport, depending on the cost of using each mode. Thus, given that the effect of the toll depends on which mode they end up using, the characterization of their policy preferences is less straightforward than for the rich. To begin, it is instructive to characterize the preferred tolls *conditional on mode choice*. Consider first a poor individual who chooses to drive. Given this choice, the toll which maximizes her utility (see (25)) is found to be:

$$\tau_L^A = \frac{n_H w_H \delta_A + n_L w_L \delta_A \left(1 - \frac{\tilde{c}}{\bar{c}}\right) - \delta_A \left(w_H - w_L\right) n_H - \frac{\bar{c} n_P}{n_L}}{1+\alpha}. \tag{35}$$

Observe that the last two terms in this expression are negative: a poor car driver necessarily wants a toll less than socially optimal. The third term captures the fact that poor car commuters benefit from reducing congestion less than the rich. The final term captures the monetary loss from the toll.

Consider next a poor public transport commuter. Her preferred toll maximizes (26). This toll just maximizes the total government revenue to be redistributed.[16] The solution is

$$\tau_L^P = \frac{n_H w_H \delta_A + n_L w_L \delta_A \left(1 - \frac{\tilde{c}}{\bar{c}}\right) - \delta_A \left(w_H - w_L\right) n_H + \frac{\bar{c} n_A}{n_L}}{1+\alpha}. \tag{36}$$

Again, the first two terms in brackets in (36) are identical to (33). The third term is negative. To understand it, consider that the revenue-maximizing toll accounts for the effect of congestion on the marginal car user (who is poor), disregarding the effect on the infra-marginal rich ones.[17] The last term is positive; it captures the fact that individuals who do not use cars benefit from the extra revenue generated by the toll. In sum, poor public transport users may want a toll above or below socially optimal.

We have just established that a poor commuter's most preferred toll is either τ_L^P or τ_L^A, depending on modal choice; we know that this choice depends on the individual's idiosyncratic cost c. Intuitively, there exists a threshold such that individuals with a high cost of accessing transit prefer τ_L^A, whereas the others prefer τ_L^P. A formal proof is provided in Appendix A.1. Figure 3 provides an illustration.

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[16] To see this, note that $\alpha\tau + \tau\left(n_A - \alpha n_P\right)/N = \left(1+\alpha\right)\tau n_A / N$.

[17] This effect is akin to Spence (1975), who shows that a monopolist firm underprovides quality if the marginal consumer values it less than the infra-marginal ones.

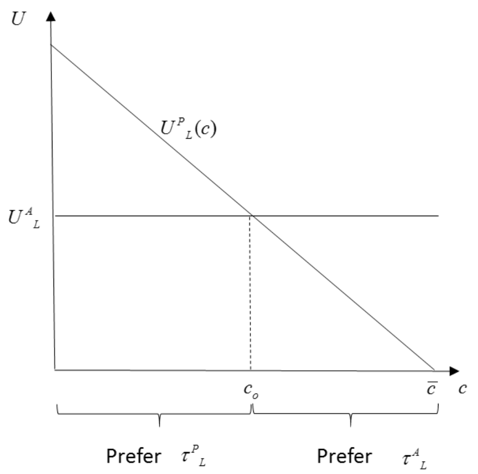

Figure 2: Access costs, modal choice and preferred tolls by poor individuals

It is easy to see that the threshold c_o decreases, all else given, with the time cost of using public transport δ_P. In Figure 3 above, increasing this parameter results in a downward shift in the $U_L^P(c)$ curve. The higher the relative cost of using public transport, the larger the share of poor individuals that drive and, hence, the more commuters prefer τ_L^A. However, we also find that the threshold c_o is independent of the earmarking parameter α (see Appendix A1).

Direct comparison of (33) - (36) suggests that, as long as $w_H - w_L$ is not too small (i.e., the rich value time substantially more than the poor), the following relations hold:

$$\tau_H > \tau^O > \tau_L^A \qquad \text{and} \qquad \tau_L^P > or < \tau^O. \tag{37}$$

The rich prefer a toll above the social optimum, because they gain disproportionately from lower congestion. The poor for whom the cost of using public transport is not too large may want a toll higher or lower than optimal, depending on how much revenue it generates. However, poor individuals who drive want a toll unambiguously below the optimum, because the reduction in congestion does not compensate them for the extra payment they have to make. Note that if the difference in time values between the two groups is small (w_H is sufficiently close to w_L) then the rich also prefer a toll less than socially optimal; in that case we have $\tau_L^P > \tau^O > \tau_H > \tau_L^A$.

The effect of earmarking on the political equilibrium is easily established. As we show in Appendix A.1, increasing α results in a smaller gap between τ^O and the preferred tolls of each group. Similar to our baseline model, earmarking reduces the divergence between the equilibrium and the socially optimal toll. We summarize our findings as follows.

PROPOSITION 2. Cordon tolls when values of time differ.

- ***If the value of time of the rich is sufficiently higher than the time value of the poor, the rich prefer a toll higher than socially optimal.***
- ***The number of poor individuals that drive and want a toll lower than optimal increases with the cost of using public transport. Unless user costs of public transport are sufficiently low, the majority of voters wants a toll lower that optimal.***
- ***Earmarking toll revenues to subsidize transit reduces the difference between the equilibrium and the socially optimal toll.***

The results suggest that differences in the value of time may play an important role in determining individual preferences for the toll. Even if they pay the toll, individuals with high values of time support it, as long as it delivers substantial reductions in congestion. However, the size of this group may not be large enough to ensure that the toll has sufficient political support. Individuals with relatively low value of time (who, given the typically skewed distribution of wages, are likely to be the majority of the population) support the toll only if the cost of using public transport is relatively small. Furthermore, earmarking toll revenues to finance transit subsidies reduces the difference between the equilibrium toll and the socially optimal one. These findings confirm that improvements to the transit system (possibly financed by toll revenues) increase political support for road pricing.

Note that -- to not overburden the model -- we ignored crowding in public transport in this subsection. Introducing it would have predictable implications for the results: what crowding does is to partly counteract the effect that lower road congestion has on public transport use. But introducing crowding would not appreciably affect the insights on voting behavior derived in this section. Crowding would only make the poor bus users less willing to support a high toll, and thus potentially aggravate the discrepancy between the optimal policy and that which the majority wants. Finally, note that the analysis of this subsection shows that crowding is not crucial for many of our qualitative results. The formulation used here also generates a well-defined conflict between the social optimum and what the majority of voters want, and it suggests that transit subsidies help reduce it.

4. The political economy of cordon tolling: capturing land market effects

In this section, we reconsider the political economy of a cordon toll, taking into account effects on the land market. Over time, residential mobility suggests that the toll will be capitalized in land rents.[18] We are interested in analyzing the implications of this effect for the political equilibrium. We first introduce land ownership arrangements into the model and analyze the effect of the toll on rents in the different zones. We then reconsider the socially optimal toll and compare it to the majority voting equilibrium.

To keep the setup as simple as possible, we return to the assumptions of the baseline model and assume equal time values. Moreover, we maintain a given urban population *N* and assume fixed lot sizes in each zone. We discuss the implications of allowing variable lot size and the possibility of urban growth at the end of this section.

4.1. Land ownership arrangements

Residents obtain income from three sources: labor, redistributed toll revenues, and landownership. The latter source is exogenous when rents are fixed in the short-run, but not so when the toll capitalizes into rents. In principle, rental income depends on whether and where a person owns land, although the distinction is often unimportant (because most people own land in the zone where they actually live; think of homeowners). Accordingly, we distinguish individuals by their rental income R^i, indexed by the superscript *i*.[19] Specifically, we consider three groups:

- Owners of land in zone *C*. The size of this group is N^c. The share of land rent that accrues to one such individual is β_c. Because all individuals in the group are identical, this share is at most equal to $\frac{1}{N^c}$; hence, $\beta_c \in (0;\frac{1}{N^c}]$. Landownership income for an individual in this group is $R^c = \beta_c r_c$.

[18] The evidence on capitalization of tolls is still scarce. The few cities that have introduced tolls have done so quite recently and, although property prices may adapt rather quickly, the effect on rents typically takes time to materialize. Not surprisingly, D'Arcangelo and Percoco (2015) find that rents inside the Milan cordon only slightly increased due to the introduction of the toll. However, Tang (2016) estimates that the introduction of the Congestion Charge in the Western Extension Zone in London increased home prices therein by 3.68%. Admittedly, not all studies find similar effects. For example, Agarwal et al. (2015) look at the effect of a small increase in the toll in Singapore. They find no effect on housing prices within the zone, but a negative effect on commercial property. More broadly, there is substantial evidence that policies affecting the cost of car travel (e.g. parking permits) have a significant effect on housing prices (see, e.g., van Ommeren et al., 2011). Finally, Franklin et al. (2016) is the only study we are aware of that explicitly provides information (for Trondheim, Norway) on the effect of cordon tolling on moving decisions. Although the toll is never the only reason for moving, the survey results do suggest it is a potentially relevant factor.

[19] If the individual resides on a parcel of land she owns, it is assumed she 'pays' a rent to herself.

- Owners of land in zone *M*. The size of this group is N^m , and the share of land rent received by one such individual is $\beta_m \in (0; \frac{Q_M}{N^m}]$. Hence, $R^m = \beta_m r_m$.
- Residents who do not own any land. We refer to this group as "renters", denoting its size by N^p. Their landownership income is $R^p = 0$.

Note the following characteristics of our specification of landownership arrangements. First, we ignore residents who own land in *S* because, in terms of policy preferences, we can treat them and renters as one group. The reason is that the toll leaves the landownership income of both groups unaffected, as r_s is exogenous. Second, our specification allows residents to own land in a different zone than the one they live in, but assumes they own land in one zone only. Third, the model captures the possibility of absentee landownership. To see this, take landownership in *C* as an example. Given the definitions above, the total fraction of land rent in *C* that accrues to urban residents is given by $\beta_c N^c$. It follows that $(1-\beta_c N^c)$ is the fraction of land owned by absentee landlords. Finally, observe that N^i and landownership shares β_i are exogenous. Of course, we have $\sum_{i=c,m,p} N^i = N$.

4.2. Effect of the toll on land rents

How does the toll change rents in the various zones? To find out, we first define utility of an individual of type *i=c,m,p* living in *j=c,m,s* by $U_j^{\,i}$:

$$U_c^{\,i} = V - r_c q_c + Y + R^i + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,P} n^2_{\ m,P}}{N}, \qquad (38)$$

$$U_m^{\,i} = V - r_m q_m + Y + R^i - \tau - \delta_{m,A}\left(n_s + n_{m,A}\right) + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,P} n^2_{\ m,P}}{N}, \qquad (39)$$

$$U_s^{\,i} = V - r_s q_s + Y + R^i - \tau - \delta_{m,A}\left(n_s + n_{m,A}\right) - \delta_s n_s + \frac{\tau(n_{m,A} + n_s) - \alpha\tau n_{m,P} + \delta_{m,P} n^2_{\ m,P}}{N}. \qquad (40)$$

The equilibrium conditions require that these utilities be invariant to where an individual resides. Thus, individuals get the same utility, up to their landownership income R^i. Furthermore, space in zones *C* and *M* must be fully occupied in equilibrium. Given the assumption of fixed lot sizes, it is obvious that the toll has no effect on population densities:

$$\frac{dn_c}{d\tau} = \frac{dn_m}{d\tau} = \frac{dn_s}{d\tau} = 0. \qquad (41)$$

The effect of the toll on land rent in the different zones is given by (see Appendix A.2 for the formal proof):

$$\frac{dr_c}{d\tau} = \frac{1}{q_c}\left(\frac{2\delta_{m,P} - \alpha\delta_{m,A}}{\delta_{m,A} + 2\delta_{m,P}}\right) \quad \text{and} \quad \frac{dr_m}{d\tau} = 0. \qquad (42)$$

Expression (42) indicates that the toll affects land rent within the cordon, but not outside. Rents in the midtown zone *M* do not depend on the toll because the latter has no effect on the commuting cost on the suburban road (due to $\frac{dn_s}{d\tau} = 0$). The effect of the toll on rent r_c in the center can be directly related to the change in generalized commuting costs on the midtown bridge. Comparing (42) and (11) we note that this change is fully capitalized in housing expenditures. Hence, we get from (42) that:

$$\frac{dr_c}{d\tau} > 0 \Leftrightarrow 2\delta_{m,P} > \alpha\delta_{m,A}. \qquad (43)$$

If $2\delta_{m,P} > \alpha\delta_{m,A}$ is positive, an increase in the toll raises generalized commuting costs to the CBD (see (11)). This is capitalized into a higher land rent in *C*. Note that this effect is mitigated when transit subsidies rise (larger α), and disappears when $\alpha = 2\delta_{m,P} / \delta_{m,A}$.

4.3 Voting on the cordon toll

We showed above that equilibrium population sizes, n_j, are exogenous to the toll. One therefore expects that the socially optimal toll is unaffected by the changes in rent: the toll can only correct for congestion in the midcity, and traffic levels generated by commuters from outside the cordon are the same as in the short-run model. To formally check this intuition, in Appendix A.3 we derive the socially optimal toll, accounting for capitalization of the toll in rents. We find:

$$\tau^{LR} = \frac{\delta_{m,A}\left(n_s + n_{m,A}\right)}{1+\alpha}, \qquad (44)$$

which is indeed identical to (16).

The observation that the effect of the toll on commuting costs is fully capitalized in rents in *C*, while leaving rents elsewhere unaffected, has implications for the preferred tolls of the different groups of voters. In Appendix A.3 it is shown that the preferred tolls of renters (group *p*) and of landowners in zone *M* are identical to that of inhabitants of zones *M* and *S* in the short-run (see Section 3):

$$\tau^p = \tau^m = \frac{\delta_{m,A}\left(n_s + n_{m,A}\right)}{1+\alpha} - \frac{(2\delta_{m,P} - \alpha\delta_{m,A})n_c}{\left(1+\alpha\right)^2}. \tag{45}$$

The intuition is obvious. Consider a renter. If she lives outside the cordon, either in zone *M* or *S*, the toll has no effect on her housing expenditures (because $\frac{dr_m}{d\tau} = \frac{dr_s}{d\tau} = 0$), but the effect on her commuting cost is the same as in the short-run scenario, see (11). If the renter lives in *C*, she avoids the toll, but its effect is fully reflected into higher housing expenditures. Either way, a renter does not internalize the effect of the toll on the income of landowners, so that preferences for the toll are the same as in the short-run scenario. The same reasoning applies to an individual who owns land in *M*, because her landownership income does not change with the toll (since $\frac{dr_m}{d\tau} = 0$).

Of course, a resident who owns land in *C* internalizes the effect that the toll has on her own land. She prefers the following toll (see Appendix A.3):

$$\tau^c = \frac{\delta_{m,A}\left(n_s + n_{m,A}\right)}{1+\alpha} + \left(\beta_c N - 1\right)\frac{(2\delta_{m,P} - \alpha\delta_{m,A})n_c}{\left(1+\alpha\right)^2} \tag{46}$$

This expression implies that the preferred toll rises in the extent of land ownership. Landowners in *C* always want a higher toll than renters and landowners in *M* (compare (46) with (45)). In fact, if they own much land in *C*, as captured by a high value of β_c, they may want a toll higher than socially optimal (the second term on the right hand side of (46) is then positive).[20] Note that if all land in the city center is owned by absentee landlords, β_c is zero, and $\tau^C = \tau^p = \tau^m$.

Summarizing, we see that

$$\tau^c > \tau^p = \tau^m \Leftrightarrow 2\delta_{m,P} - \alpha\delta_{m,A} > 0 \Leftrightarrow \frac{dr_c}{d\tau} > 0 \tag{47}$$

[20] This toll differs from the desired toll of inhabitants of *C* in the short-run. To see this most clearly, assume no earmarking. In the short-run, central city inhabitants want a high toll because they receive part of the redistributed revenues. In the long run, however, landowners in *C* want a high toll only because commuting costs are capitalized into rents. This implies that they want a high toll only if they own a sufficiently large lot of land.

Unless central landowners are the absolute majority of the population, the toll preferred by the median voter is $\tau^{p} = \tau^{m}$. This toll is less than socially optimal if and only if the toll raises central city land rent:

$$\tau^{p} = \tau^{m} < \tau^{LR} \Leftrightarrow 2\delta_{m,P} - \alpha\delta_{m,A} > 0 \Leftrightarrow \frac{dr_c}{d\tau} > 0 \,. \tag{48}$$

The toll redistributes welfare from renters and landowners outside the cordon to landowners inside. Renters and landowners in *M* ignore the capitalization effect on land rent in *C,* but a welfare maximizing government does not. Thus, residents generally fail to fully internalize the social benefit of the toll, unless they own a (sufficiently large) lot of land within the cordon. However, note that the last term in (45) and (46) decreases with α. Transit subsidies weaken the increase in commuting costs that comes with the toll and, thus, its long-run effect on land rent. Hence, they reduce the redistributive effects that generate opposition to the toll. These observations immediately lead to the following Proposition.

PROPOSITION 3. The cordon toll and the land market

- ***a. The cordon toll raises land rents within the cordon and leaves rents outside the cordon unaffected.***
- ***b. With lump-sum redistribution of the toll revenues (*** $\alpha = 0$ ***), the equilibrium toll is less than socially optimal, unless residents owning land within the cordon are the majority of the population.***
- ***c. Using toll revenues to subsidize transit (*** $\alpha > 0$) ***mitigates opposition to the toll.***

Proposition 3 suggests an additional explanation for the fact that city governments tend to underprice congestion. In practically all the real-world examples of implemented and contemplated tolls, the cordon encompasses the most central area of the city, with a high density of office and commercial buildings as well as several amenities (e.g. parks or historical buildings). Land within the cordon is therefore generally scarce and highly expensive. Hence, it is unlikely that residents that own land within that area constitute the majority of the population (see footnote 3 above for evidence). Proposition 3 then suggests that the political process likely results in underpricing of congestion. However, transit subsidies mitigate the effects of the toll on the land market, and therefore alleviate the redistributive forces that induce the majority of voters to oppose tolling.

As in earlier sections, a discussion of the main assumptions is in order. First, we assumed fixed lot sizes; this simplified the derivations substantially. However, introducing endogenous lot sizes would have no first-order effect on our main results, because it does not alter the key mechanism whereby commuting costs capitalize into the price of land. In the online appendix, we introduced endogenous lot size into the model. The results were more complex and harder to interpret, but the main insights on voting behavior were not appreciably affected.

Second, we assumed a closed city in the sense that city population N is fixed. But pricing of car use may itself affect city size.[21] To the extent that it makes the city more efficient, the toll potentially attracts new residents as well as firms. This has two clear consequences that our model ignored, and that work in opposite directions. One is that it partially destroys the gains from reduced congestion by attracting new traffic. The other is that city growth may bring additional benefits from agglomeration. It is a priori unclear which effect will dominate.

Third, the model of this section ignored heterogeneity in incomes and time values. In the long run, households of different incomes may sort in different zones. However, it would be quite complex to extend the model to account for this, while also including modal choice. In an earlier version of the paper, we introduced income heterogeneity in a long-run model with variable lot size; the car was the only travel mode and toll revenues were lump sum redistributed by assumption. We considered two scenarios, a "European type" city where the rich live in the center (Paris, London, etc.) and the poor in the suburbs, and a "US type" city where the rich live in the suburbs. In both scenarios, we found that the poor majority prefers a toll below the optimum. In the first (rich-in-center) scenario, they do so because they have to pay the toll while commuting, but the revenues are redistributed also to the rich. In the second scenario, the poor in the center suffer from the increase in rents, unless they own the land they occupy, which is unlikely given that this land is located in the center of the city (see our arguments above).

5. The political economy of toll location

We have assumed so far that the cordon is placed between zones M and C. However, the results of the previous sections have pointed at the conflict between residents (or landowners) within and outside the cordon. Intuitively, because preferences strongly differ between these groups, the location of the toll may be used as a lever to generate support for its introduction. To explore this issue, in this section we report some results on the political economy of toll location. We compare voter preferences for a cordon close to the center (between M and C) versus one placed further away (between zones S and M). We denote these

[21] For example, Takayama and Kuwahara (2017) analyze bottleneck congestion in a monocentric city, showing that, depending on the distribution of schedule-delay costs, a time-varying toll may lead the city to expand outwards. As they do not consider a cordon toll, however, their results may not be directly applicable our setting,

tolls by τ_m and τ_s respectively (see Figure 3). The key difference is that all commuters from *M* and *S* pay the midtown toll, whereas only commuters from *S* pay the suburban toll. This has important implications for social welfare (Mun *et al.*, 2003). Moreover, it also affects the political equilibrium.

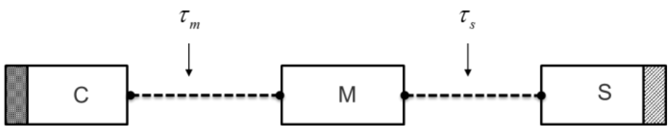

Figure 3: Tolls on the midtown and suburban bridge

Is it easier to get a political majority for a small versus a larger cordon? Unfortunately, it is very hard to provide a general theoretical answer to this question. The answer depends on the level of the two tolls, and the analysis of the outcomes when residents jointly vote on toll location and toll level is highly complex and often generates no equilibrium outcome (Persson and Tabellini, 2000). In Appendix C (available online) we do derive one set of interesting -- but admittedly quite restrictive -- theoretical results. We consider an initial situation with no toll and assume the government contemplates imposing a small toll, either on the midtown or on the suburban bridge. In both cases, we analyze whether residents would support the tolls, and whether they would favor the midtown or suburban one. We find that, except in rather unrealistic conditions, a majority of voters prefers the midtown toll, both in the short- and long-run scenario. The intuition is that the midtown toll generates more revenue and is more effective at reducing congestion.

Of course, voting outcomes on small tolls offer little guidance for evaluating outcomes on non-marginal toll levels. Given the impossibility of further theoretical comparisons, in the next section we use numerical analysis to cast some light on this issue, confirming the above statements.

6. Numerical Application

A numerical implementation of our model, using data for the city of Milan, serves to illustrate the results.[22] We start by briefly introducing the functional forms and the main parameters (how these were determined is explained in Appendix B), then we discuss the results. Additional numerical results are in Appendix D (available online).

[22] Rotaris et al. (2010) provide a comprehensive description of the Milan cordon scheme.

We assume the travel cost functions from *M* to the CBD are $\delta^0{}_{m,A} + \delta_{m,A}\left(n_s + n_{m,A}\right)$ and $\delta^0{}_{m,p} + \delta_{m,p} n_{m,p}$ for car and public transport, respectively; the cost function is $\delta^0{}_s + \delta_s n_s$ for car trips between *S* and *M*.[23] The calibrated parameters are $\delta^0{}_{m,A} = 4.872$, $\delta_{m,A} = 0.0194$, $\delta^0{}_{m,p} = 11.433$, $\delta_{m,p} = 0.0097$, $\delta^0{}_s = 12.472$ and $\delta_s = 0.0155$. Note that these cost functions express the commuting cost (in euros) per day. We assume each commuter takes two daily trips, i.e. from home to the CBD and back. We also assume there is one commuter per household.

We divide the city in three zones. The central one is identified as the area within the cordon in Milan (the "Cerchia dei Bastioni"). However, there is no natural way to define a boundary between the midtown and suburban zone. Hence, we assume that the midtown zone coincides roughly with the area between the cordon and the route of circular bus line 90/91 (which is a major bus line in Milan, see Appendix B). We take 2007 as our baseline (no-toll) year, because cordon pricing was activated in Milan on January 1st 2008. Using data provided by the municipality, we calculate the number of households in each zone: $n_c = 53,530$, $n_m = 269,910$, $n_s = 272,760$. Note that, because we assume fixed lot sizes, these populations are exogenous in both the short- the long-run scenario.

Lot sizes for zones *C* and *M* were computed as $q_i = S_i / n_i$, where S_i is the available residential space in zone *i*. The S_i's in zones *C* and *M* are imputed as follows. We normalize the size of the central zone to one, and we assume the size of the midtown zone equals 8.81, consistent with the relative sizes of the areas within the cordon and the midtown zone we identified above.[24] Therefore, we obtain that $q_c = 0.0187$ and $q_m = 0.0326$. We finally impute lot size in the suburban zone based on statistics provided by the city of Milan; they suggest that lot sizes in the suburbs are roughly 60% larger than in the central city. Hence, we assume $q_s = 0.05$.

We calibrate the rental price of suburban land using data from the Italian Internal Revenue Agency, obtaining a daily rent of 0.332 euros per square meter (see Appendix B for details). Finally, concerning landownership, we assume that each resident-landowner in zone *C* and *M* owns a parcel of land equal to the size of a residential lot in the respective zone. That is $\beta_c = q_c = 0.0187$ and $\beta_m = q_m = 0.0326$. Based on homeownership data reported by ISTAT

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[23] We assume travel cost functions have a positive intercept to facilitate the calibration. Including these intercepts in the analytical framework does not affect our previous results.

[24] The size of the area within the cordon in Milan is approximately 8 sq. kms, whereas the size of the area enclosed between the cordon and the circular bus line is 70,5 sq. kms.

(2011) for Milan, we assume the number of households that own land in zones *C* and *M* equals 33% and 50% of all households residing in that zone, respectively.

Turning to the result, we first consider the short-run scenario with immobile households and, therefore, fixed rents. Table 1 reports the results for four different cases: the no-toll case which serves as the baseline, and three additional scenarios characterized by a different value of α. Specifically, we consider $\alpha = 0$ (full lump-sum redistribution), $\alpha = 0.5$ (mild increase of transit subsidies with the toll) and $\alpha = 1$ (strong increase). Note that our calibrated parameters imply that $\alpha = 1$ is equivalent to $\alpha = 2\delta_{m,P} / \delta_{m,A}$. This value plays a crucial role in the analytical model, see Sections 3 and 4 above. The leftmost panel of Table 1 describes the no-toll equilibrium; 18.7% of commuting trips are by public transport, the rest are car trips.[25] The generalized commuting cost from the midtown zone to the CBD and back is 13.4 euros per day. Public transport revenues amount to just over hundred thousand euros per day. The second panel of the table indicates that, with lump-sum redistribution, the preferred toll by the median voter (a midtown or suburban resident) is approximately 5 euros per day; this is roughly 13% lower than the socially optimal toll of 5.7 euros. By contrast, residents of the central zone *C* want a toll equal to 6.5 euros, about 14% higher than the optimal toll.[26]

The implications of tying the toll to transit subsidies are clear. When $\alpha = 0.5$, commuting costs from the midtown to the central city still increase with the toll. Consistently with our analytical findings, the optimal toll is then higher than the majority-preferred one, but the difference shrinks to about 5%. Finally, when $\alpha = 2\delta_{m,P} / \delta_{m,A} = 1$, the cost of commuting to the CBD does not increase with the toll, and all voters prefer the socially optimal toll. Note that, as pointed out above, welfare at the optimal toll is independent of how the revenues are used.

Table 1 : Numerical results, short-run model (fixed rents)

		α=0			α=0,5			α=1		
	NO TOLL	OPTIMAL TOLL	TOLL C	TOLL M,S	OPTIMAL TOLL	TOLL C	TOLL M,S	OPTIMAL TOLL	TOLL C	TOLL M,S
Car trips	440.7	293.8	272.8	311.6	293.8	272.8	299.7	293.8	293.8	293.8
Transit trips	102.0	248.9	269.9	231.0	248.9	269.9	242.9	248.9	248.9	248.9
Toll	0	5.7	6.5	5.0	3.8	4.3	3.6	2.8	2.8	2.8
Transit Fare	1.0	2.4	2.6	2.2	0.5	0.4	0.5	0.0	0.0	0.0
Gen. price from M to CBD	13.4	16.3	16.7	15.9	14.4	14.5	14.3	13.4	13.4	13.4
Gvmt. Net Revenues	100.8	2271.9	2480.1	2075.1	1242.4	1303.3	1220.6	727.7	727.7	727.7
Social Welfare	167131	167758	167701	167705	167758	167720	167757	167758	167758	167758

Note: Daily quantities. Trips expressed in thousands, prices in euros, revenues in thousands of euros.

[25] The modal share of cars we obtain is larger than it was prior to road pricing in Milan (between 47% and 66%, depending on how one defines the city boundaries). This discrepancy is due to our assumption that all suburban commuters use automobiles. Furthermore, we ignore alternative travel modes (e.g. biking).

[26] Our model is too stylized to provide an accurate estimate of the optimal toll in Milan. Nevertheless, the values we obtain are, reassuringly, of the same order of magnitude as the toll currently in place, equal to 5 euros per day.

Next we present the results with mobile households and rent capitalization, see Table 2. Recall that landownership (as opposed to residence) determines the differences in voter preferences in the long run. We report the socially optimal toll and the preferred tolls by each group for the same revenue redistribution policies considered in Table 1. Moreover, we report equilibrium land rents in zones *C* and *M*.

If revenues are entirely redistributed lump sum ($\alpha = 0$), or if the public transit subsidy increases mildly with the toll ($\alpha = 0.5$), the results suggest that all groups prefer a lower toll than socially optimal, except those who own land in the central zone. Indeed, central land rent increases substantially with the toll. For instance, when $\alpha = 0$ the adoption of the socially optimal toll leads to an increase of central land rent from 1.5 to 1.67 euros/m^2-day, i.e. about 12%. The increase is limited to about 4% when $\alpha = 0.5$. Finally, when $\alpha = 1$, the preferred tolls of all groups converge to the socially optimal one.

Table 2: Numerical results, model with rent capitalization

		α=0			α=0,5			α=1		
	NO TOLL	OPTIMAL TOLL	TOLL C	TOLL M,P	OPTIMAL TOLL	TOLL C	TOLL M,P	OPTIMAL TOLL	TOLL C	TOLL M,P
Car trips	440.7	293.8	272.8	300.5	293.8	272.8	296.0	293.8	293.8	293.8
Toll	0.0	5.7	6.5	5.3	3.8	3.9	3.7	2.8	2.8	2.8
Gen. price from M to CBD	13.4	16.3	16.7	16.0	14.4	14.7	14.3	13.4	13.4	13.4
Land rent zone C	1.7	1.85	1.87	1.84	1.75	1.73	1.75	1.70	1.70	1.70
Land rent zone M	0.6	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Social Welfare	157730	158357	158344	158310	158357	158120	158341	158357	158357	158357

Note: Daily quantities. Trips expressed in thousands, residents in thousands of households, prices in euros.
The columns "Toll M,P" report results for the scenario where the toll preferred by resident landowners in M and pure renters is implemented.

Finally, we report results on the desired toll location by different groups. Specifically, we compare voter utilities when the *socially optimal* tolls on the midtown and the suburban bridges are introduced (assuming lump-sum revenue distribution). The results are in Tables 3 and 4.[27]

Table 3 compares – for the short-run model -- the no-toll scenario with an optimal toll on the midtown and the suburban road. The former generates more revenues, because it applies to all car commuters. Therefore, because central city residents only care about net toll revenues (they do not have to cross any zone to commute to the CBD), they prefer the midtown toll.

[27] Given our assumptions, the suburban toll does not change the number of car trips from the suburbs when $\alpha = 0$. Hence, congestion on both roads is unaffected. It also follows that social welfare is invariant with this toll. The suburban toll we focus on in Tables 3 and 4 is equal to the marginal external cost on the suburban road. This choice is arbitrary, but is not crucial for our arguments: our results (not reported for reasons of space) show that central and suburban residents prefer the midtown toll to any suburban toll below 8.

Furthermore, this toll induces a stronger reduction in midtown car traffic than the suburban one. Hence, suburban residents (who have to pay the toll regardless of its location) are better off with the midtown toll. Finally, in principle, midtown residents can favor either toll: they do not pay the suburban toll, but the midtown toll generates more revenue. In our example, it turns out that they prefer the suburban toll. Nevertheless, because central and suburban residents are more than half the total population, a toll located closer to the city center is more likely to obtain the support of a majority of voters than one placed further out.[28]

Table 3: toll location results, short-run model (fixed rents)

	NO TOLL	MIDTOWN TOLL	SUBURBAN TOLL
Toll	0.0	5.7	4.2
Transit Fare	1.0	2.4	1.0
Gen. price from M to CBD	13.4	16.3	13.4
Gen. price from S to CBD	30.1	33.0	34.3
Gvmt. Net Revenues	100.8	2271.9	1253.7
Welfare			
Central Residents	300.2	303.8	302.1
Midtown Residents	286.8	287.6	288.7
Suburban Residents	270.1	270.9	267.8
Social Welfare	167131	167758	167131

Note: daily quantities. Trips expressed in thousands, prices in euros, revenues in thousands of euros.

Table 4 provides the same comparison as Table 3, but for the scenario where the toll affects rents. The midtown toll is preferred over the suburban toll by owners of land in the central city *C* as well as by renters; landowners in the midtown *M* prefer the suburban toll. The intuition is that the suburban toll increases land rent in the midtown zone, contrary to the midtown toll. Assuming renters plus central city landowners are the majority of the population,[29] the model suggests that the midtown toll is more likely be adopted.

[28] Table 3 also indicates that all groups are better off with the optimal midtown toll than with no toll. However, note that, in line with our analytical model, we obtain these results ignoring the toll's operating costs. In Appendix D (available online), we provide an extended version of this table (Table D.1). When one accounts for operating and implementation costs, the majority of residents are worse off with the toll than without it, although social welfare increases. Several studies have shown that toll implementation costs are not negligible. See, e.g., Prud'homme and Bocarejo (2005) for London and Rotaris et al. (2010) for Milan. Similar conclusions apply to the long-run scenario (Table D.2).

[29] Our data suggest that this condition does indeed apply in Milan. See Table B.1 in Appendix B below.

Table 4: toll location results, model with rent capitalization

	NO TOLL	MIDTOWN TOLL	SUBURBAN TOLL
Toll	0.0	5.7	4.2
Transit Fare	1.0	2.4	1.0
Gen. price from M to CBD	13.4	16.3	13.4
Gen. price from S to CBD	17.6	20.5	21.9
Gvmt. Net Revenues	100.8	1691.6	673.4
Welfare			
Resident-landowner C	276.3	279.9	278.2
Resident-landowner M	266.2	267.0	268.2
Renter	235.4	236.2	233.2
Social Welfare	146834	147461	146834

Note: daily quantities. Trips expressed in thousands, prices in euros, revenues in thousands of euros.

Summing up, both the theoretical argument suggested above and the numerical results for Milan suggest that cities may place cordons relatively close to the center for reasons beyond technical feasibility. Our results suggest that a majority of urban voters prefers a cordon covering a small area to one covering a larger area. This conclusion is consistent with the fact that most existing (and contemplated) tolls encompass a relatively small area around the city center (see the examples of London, Stockholm, Milan, etc.).

7. Concluding remarks

This paper studied the political economy of cordon tolls in a stylized model a city consisting of a central, a midtown and a suburban area. The model identified different potential interrelated conflicts: between commuters within and outside the cordon, between car and public transport users, between rich and poor people and, when the toll is capitalized into rents, between landowners and renters. We found several arguments as to why voter support for tolls is typically low. In the short run, voters located outside the cordon want a toll lower than the socially optimal level. Furthermore, although the rich gain from the toll, poor car commuters fail to internalize its social benefits, and thus want a toll below the optimum. When changes in commuting costs capitalize into land prices, we find that only voters who own land within the cordon may support the toll. However, a common finding from all scenarios is that earmarking toll revenues to public transport subsidies mitigates opposition. Finally, we show that a cordon covering a small area around the center is more likely to be approved than one placed further out. A numerical application of the model to the city of Milan confirmed the theoretical predictions.

In future work, one may relax some of the assumptions of our model. For example, one may consider a broader set of decisions by the public transit agency to include pricing, frequency, network density, etc. Moreover, one may relax the assumption of a closed city. In the long run, if the toll does make the city’s transport system more efficient, it may also attract new firms and residents. This effect may bring additional benefits from agglomeration, although it may also partially negate some of the gains of reduced congestion. Finally, some assumptions underlying our model have to be confirmed by empirical research. For example, although the available empirical evidence is consistent with cordon tolls affecting land markets, the precise effect of a toll on prices within and outside the cordon has not yet been widely documented. When more real world cordon tolls are introduced one expects this gap in the empirical literature to be filled soon.

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Appendix A: proofs of results in the text

A1. Characterization of the threshold c_o.

When she commutes by car and τ_L^A is implemented, a poor individual characterized by idiosyncratic cost *c* obtains utility

$$U_L^A = V - \tau_L^A - w_L \delta_A n_{A,L}^A + \frac{\tau_L^A \left(n_{A,L}^A - \alpha n_{P,L}^A\right)}{N} = V - w_L \delta_A n_{A,L}^A - \frac{\tau_L^A \left(1+\alpha\right) n_{P,L}^A}{N}. \quad (49)$$

In this expression, $n_{A,L}^A$ (resp. $n_{P,L}^A$) denotes the number of car (resp. public transit) users when τ_L^A is adopted. The same individual obtains instead

$$U_L^P(c) = V - f + \alpha\tau_L^P - w_L \delta_P - c + \frac{\tau_L^P \left(n_{A,L}^P - \alpha n_{P,L}^P\right)}{N} = V - f - w_L \delta_P - c + \frac{\left(1+\alpha\right) \tau_L^P n_{P,L}^P}{N}, \quad (50)$$

when she commutes by public transport and τ_L^P is implemented ($n_{A,L}^P$ is the number of cars users with τ_L^P implemented; similarly for public transport users). Therefore, the individual prefers to have the government adopt τ_L^A (and commute by car) if and only if $U_L^A \geq U_L^P(c)$. Because the left-hand side of this inequality is independent of *c* while the right-hand side is strictly decreasing in *c*, there exists a threshold c_o such that when $c \geq c_o$, the individual prefers τ_L^A, whereas she prefers τ_L^P otherwise.

It is easy to show that c_o is independent of revenue use, as captured by α. To do so, we first show that $n_{A,L}^A \equiv n_A(\tau_L^A)$ and $n_{P,L}^A \equiv n_P(\tau_L^A)$ are independent of α. To see this, replace (35) in (29) and solve for $\tilde{c}$. Because the solution depends only on exogenous parameters, but not on α, it has to be that neither $\tilde{c}$, n_A nor n_P vary with α when evaluated in τ_L^A. We can follow the same reasoning to show that n_A and n_P are invariant with α when evaluated in τ_L^P, τ_H and τ^{FB}. This implies that the numerator on the right hand side of expressions (33) - (36) must be invariant with α as well. Hence, we conclude that the absolute value of the difference between τ^{FB} and any of the preferred tolls must be decreasing with α. Moreover, it implies that c_o is invariant with α as well. Indeed, we have just shown that n_A and n_P are invariant with α when evaluated in τ_L^A and τ_L^P. By replacing these tolls in (49) and (50), respectively, one immediately concludes that the resulting expressions for U_L^A and $U_L^P(c)$ do not depend on α. Therefore, c_o cannot depend on it either.

A2. Derivation of (42) **and** (41)

We begin by providing the formal conditions required by the equilibrium. First, space in zones *C* and *M* be fully occupied. Hence,

$$n_c q_c = 1 \quad \text{and} \quad n_m q_m = Q_M . \tag{51}$$

Furthermore, in equilibrium utility must be invariant with location, i.e.

$$U_c^{\ i} = U_m^{\ i} = U_s^{\ i} = U^i; \quad i = c, m, p. \tag{52}$$

We have, using (38)-(40) and (52), that:

$$U^c = U^p + R^c \quad \text{and} \quad U^m = U^p + R^m . \tag{53}$$

The utility of a resident-landowner in the center *C* or the midtown zone *M* is identical to that of a renter up to R^i.

To find the effect of the toll on rents, use (52) in (38)-(40); this gives:

$$r_c q_c - r_m q_m = \tau + \delta_{m,A}(n_{m,A} + n_s), \tag{54}$$

$$r_m q_m - r_s q_s = \delta_s n_s . \tag{55}$$

Given that the right hand side of (54) and (55) is strictly positive and $q_c < q_m < q_s$, it is easily shown that $r_s < r_m < r_c$ in equilibrium. The rental price of land decreases away from the center.

Starting from (51) and given the fact that q_c and q_m are exogenous, one immediately gets that $\frac{dn_m}{d\tau} = \frac{dn_c}{d\tau} = 0$. Then (41) follows immediately. Because q_m, q_s and r_s are exogenous, differentiation of (55) shows that $\frac{dr_m}{d\tau} = 0.$ Using this result and differentiating (54), noting that q_c is also exogenous, we find:

$$q_c \frac{dr_c}{d\tau} = 1 + \delta_{m,A}\left(\frac{dn_{m,A}}{d\tau} + \frac{dn_s}{d\tau}\right). \tag{56}$$

The last term in brackets is zero by (41). Using the Wardrop condition in (9) and noting that $\frac{dn_m}{d\tau} = 0$, we get

$$\frac{dn_{m,A}}{d\tau} = -\frac{dn_{m,P}}{d\tau} = -\frac{(1+\alpha)}{\delta_{m,A} + 2\delta_{m,P}}. \tag{57}$$

Replacing this expression in (56) and rearranging, we get $q_c \frac{dr_c}{d\tau} = \frac{2\delta_{m,P} - \alpha\delta_{m,A}}{\delta_{m,A} + 2\delta_{m,P}}$, from which we obtain (42).

A3. Optimal and preferred tolls

Social welfare consists of the sum of utilities of all urban residents, plus total land rent (whether accruing to residents or absentee landlords). Using the fact that individual utility is independent of location in equilibrium (see (52)), we can write social welfare as follows:[30]

$$\underset{\tau}{Max} \quad N\left\{ v(q_c) - r_c q_c + \left[\frac{\tau\left(n_{m,A} + n_s\right) - \alpha\tau n_{m,P} + \delta_{m,P} n^2{}_{m,P}}{N} \right] \right\} + r_c + r_m Q_m. \tag{58}$$

Given (41) and (42), the first-order condition for problem (58) writes

$$\frac{dW}{d\tau} = -Nq_c \frac{dr_c}{d\tau} + \tau\left[(1+\alpha)\frac{dn_{m,A}}{d\tau} \right] + (n_{m,A} + n_s) - \alpha(n_m - n_{m,A}) + 2\delta_{m,P} n_{m,P} \frac{dn_{m,\mathrm{P}}}{d\tau} + \frac{dr_c}{d\tau} = 0.$$

Using (1), (51) and (57), we can rearrange this expression as follows

$$\tau \frac{(1+\alpha)^2}{\delta_{m,A} + 2\delta_{m,P}} = -\left(n_s + n_m\right)\frac{dr_c}{d\tau} q_c + \left(n_s + n_{m,A} - \alpha n_{m,\mathrm{P}}\right) + n_{m,\mathrm{P}} \frac{2\delta_{m,P}(1+\alpha)}{\left(\delta_{m,A} + 2\delta_{m,P}\right)} \tag{59}$$

Making use of (42) and rearranging, we get

$$\tau(1+\alpha)^2 = -\left(n_s + n_m\right)\left(2\delta_{m,P} - \alpha\delta_{m,A}\right) + \left(n_s + n_{m,A} - \alpha n_{m,\mathrm{P}}\right)\left(2\delta_{m,P} + \delta_{m,A}\right) + 2\delta_{m,P} n_{m,\mathrm{P}} (1+\alpha).$$

From which we obtain (44).

[30] To save notation, we omit the value of suburban land in social welfare. This omission is harmless because this rent is exogenous, equal to the price of vacant land beyond the city boundary.

To derive (45), the preferred toll by renters, note that the FOC of the maximization problem of a renter is

$$\frac{dU^p}{d\tau} = -Nq_c \frac{dr_c}{d\tau} + \tau\left[(1+\alpha)\frac{dn_{m,A}}{d\tau}\right] + (n_{m,A} + n_s) - \alpha(n_m - n_{m,A}) + 2\delta_{m,P} n_{m,P} \frac{dn_{m,\mathrm{P}}}{d\tau} = 0. \qquad (60)$$

As in the previous derivation, we can rearrange (60) as follows:

$$\tau(1+\alpha)^2 = -N\left(2\delta_{m,P} - \alpha\delta_{m,A}\right) + \left(n_s + n_{m,A} - \alpha n_{m,\mathrm{P}}\right)\left(2\delta_{m,P} + \delta_{m,A}\right) + 2\delta_{m,P} n_{m,\mathrm{P}}\left(1+\alpha\right).$$

Working out, using analogous steps as before, we find (45). The derivation of (46) follows identical steps, except that $\frac{dU^c}{d\tau} = \frac{dU^p}{d\tau} + \beta_c \frac{dr_c}{d\tau}$.

Appendix B: data for the numerical application

The data and parameters used in the numerical application to Milan are summarized in Table B.1. In the remainder of this appendix, we explain how the data were collected and how the parameters were determined.

Travel costs

We compute the slope of the travel cost function for cars entering the central zone using data from Rotaris et al. (2010, 2012). They report an average speed of private vehicles within the cordon of 20 km/h in 2007, the year prior to the introduction of road pricing in Milan, and 21 km/h in 2009. They also report a decrease in private vehicle entries in the cordon of 19,162 vehicles per year after toll introduction. Based on an average trip length computed using Google Maps, we assume an average length of a trip from *M* to *C* equal to 5 km. Rotaris et al. (2010) report a value of travel time in Milan equal to 15.59 Euros/h. Because speed limits on inner roads in Milan never exceed 50 km/h and are often lower, we assume a free-flow travel speed of 32km/h. Finally, we account for the fact that each working day entails two commuting trips. Using this information, we compute the intercept and the slope of the congestion function as, respectively:

$$\delta^0{}_{m,A} = 2 \cdot \frac{5}{32} \cdot 15.59 = 4.872 \text{ [€/day]},$$

$$\delta_{m,A} = 2\cdot 5\cdot 15.59\cdot\left(\frac{1}{20}-\frac{1}{21}\right)\cdot\frac{1,000}{19,162} = 0.0194\,[€/1000\text{veh-day}].$$

These parameters imply that, in our baseline scenario, the average one-way commuting time from *M* to the CBD is 25.8 minutes.

To compute $\delta^0{}_s$, we assume a trip length of 20 km from the suburban to the midtown zone (this length is consistent with information provided by Google Maps, see Table B.1). Outer roads in the city of Milan have speed limits that vary from 50 to 80km/h. However, most of these roads cross rather densely populated areas, so we assume the average free flow speed on the suburban road is 50km/h. This implies a one-way free flow travel time from the edge of the city to the midtown zone of 0.4 hours (24 minutes). We get $\delta^0{}_s = 2\cdot\frac{20}{50}\cdot 15.59 = 12.472$ [€/day].

We did not find any data on congestion on Milan's suburban roads. We therefore compute δ_s as follows. We assume the duration of a one-way trip on the suburban road in the no-toll baseline scenario (with $n_s = 272,760$ suburban car commuters, see below) is 32 minutes.[31] Therefore, the one-way extra travel time due to congestion on the suburban road is 8 minutes or approximately 0.136 hours. Because there are $n_s = 272,760$ commuters in the baseline, we have therefore that $\delta_s = 2\cdot 15.59\cdot 0.136\cdot\frac{1,000}{272,760} = 0.0155$ [€/1000veh-day]. This value corresponds to 0.8 times $\delta_{m,A}$.

Although anecdotal evidence of crowding on public transport in Milan exists,[32] we were unable to find any quantitative study. Therefore, we draw on the literature to evaluate $\delta_{m,p}$. To our knowledge, the only study to provide an aggregate comparison of road and public transit congestion costs is Prud'homme et al. (2012), based on data from Paris. In Annex A, they show that, in the optimal allocation, the slope (with respect to the number of users) of the transit user cost function is 0.42 times that of the road user cost function. Based on this value, because road congestion in Paris is most likely stronger than in Milan, we assume that $\delta_{m,p}$ is 0.5 times $\delta_{m,A}$. Hence, $\delta_{m,p} = 0.0097$ [€/1000pax-day]. Finally, we compute $\delta^0{}_{m,p}$ assuming a trip length of

[31] This assumption implies, in our baseline scenario, a one-way commuting time from *S* to the CBD of approximately 58 minutes, and an average one-way commuting time of approximately 37 minutes per commuter. These values are consistent with the literature on cordon tolling. For instance, De Lara et al (2013) report an average commuting time of 38 minutes in the no toll scenario of their simulation model based on Paris. Tikoudis et al. (2015) report an average one way commuting time of 36 minutes in the no toll scenario.

[32] http://www.ilgiorno.it/rho/cronaca/vanzago-pendolari-trenord-affollamento-1.1469245 (in Italian).

5kms, an average transit speed of 15km/h,[33] and adding 10% to the resulting travel time to account for waiting time and access costs. We obtain $\delta^0_{m,p} = 2 \cdot \frac{5}{15} \cdot 15.59 \cdot 1.1 = 11.433$ [€/day].

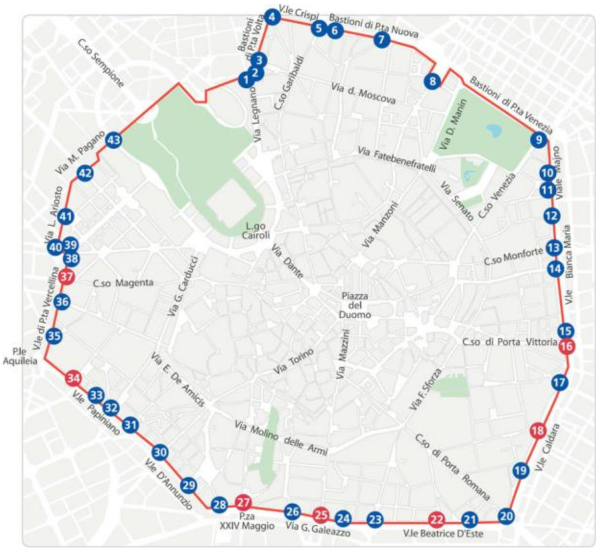
Table B.1: Data for the numerical application

PARAMETER	VALUE	SOURCE
Trip length midtown to CBD [kms]	5	Google Maps, trip from via G.Colombo to P.zza Duomo
Trip length suburban to midtown [kms]	20	Google maps, trip from Tangenziale Nord to p.ta Venezia
POPULATION		
Central zone [2007 inhabitants]	107,067	Comune di Milano
Midtown [2007 inhabitants]	539,821	
Suburban [2007 inhabitants]	681,900	
Avg. household size, central and midtown zone	2	Assumed based on city statistics (see text)
Avg. household size, suburban zone	2.5	
CAR		
Free flow speed midtown to CBD [km/h]	32	Assumed based on inner city speed limits
Free flow speed suburban to midtown [km/h]	50	Assumed based on outer city speed limits
Value of travel time [2008 euros/h]	15.59	Rotaris et al. (2010, Appendix C)
Average speed within central zone 2007 (pre-Ecopass) [km/h]	20	Rotaris et al. (2010, Appendix G)
Average speed central zone, post Ecopass [km/h]	21	Rotaris et al. (2010, App. G), Danielis et al. (2012, App. C)
Change avg. daily entries in cordon, pre vs post Ecopass [veh./day]	19,162	Computed from Rotaris et al. (2010, Appendix A and B)
Ratio suburban to midtown congestion term	0.8	Assumed (see text)
TRANSIT		
Average transit speed midtown to CBD [km/h]	15	Assumed[a]
Ratio transit congestion to midtown road congestion slope	0.5	Assumed (see text)
Coefficient increase access - wait time cost	1.1	Assumed[b]
LAND MARKET		
Surface ratio midtown vs central zone	8.81	8 sqkm within cordon, 78,5 sqkm within bus line n.90/91
Rental price suburbs [euros/sqm per month]	6.99	Agenzia del Territorio (see text)
Working days per month [2007 average]	21	Istat, Annuario Statistico 2007
Share of resident-landowner households in C	0.33	Assumed based on ISTAT (2011)
Share of resident-landowner households in M	0.5	
Resident-landowner households in C (thousands)	17.67	
Resident-landowner households in M (thousands)	134.96	
a) Using average travel speed of surface (9.25km/h) and underground (29km/h) transit within central area		
b) Multiplies the intercept of the transit travel time cost to give total travel cost		

Population and geographical parameters

The Milan road pricing scheme covers an area of about 8 km^2, enclosed within a circular road (the "Cerchia dei Bastioni"). There is no clearly defined boundary between midtown and suburban zones. Hence, we assume the midtown zone coincides roughly with the area between the cordon and the track of a major circular bus line (n.90). See Figure B.1. Although the boundary of the midtown zone is not a perfect circle, we assume it is circular with a radius of 5 kms. Thus, its size equals 8.81 times that of the central zone. Thus, we set $Q_M = 8.81$.

[33] This value is based on average travel speed within the cordon zone of surface transport (9.25km/h, as reported for 2009 by Rotaris et al., 2010), and of underground rail transport (29km/h, as reported on Wikipedia).



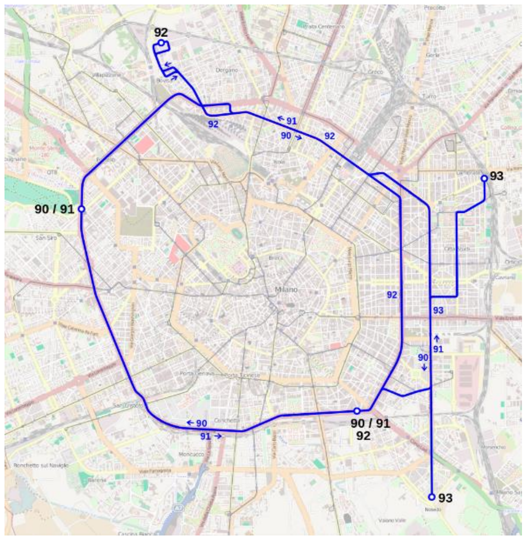


Figure B.1: cordon area in Milan (left) and track of Bus 90/91 line (right)

To compute the population in each zone in the baseline scenario, we take 2007 as our reference year, because cordon pricing in Milan was activated on the 1st of January of 2008 (the so-called "Ecopass" scheme). Using a database provided by the Milan municipality,[34] we find that there are 107,067 inhabitants in the central zone, 539,821 in the midtown and 681,900 in the suburban zone. To compute the number of households, we assume, based on information provided by the Milan municipality, an average household size of 2 in central and midtown zone, and 2.5 in the suburbs.[35] As a result, we obtain the following number of households in each zone: $n_c = 53,530$, $n_m = 269,910$, $n_s = 272,760$.

Land market

The rental price of land in the central and midtown zones are endogenous in our long run model. However, the rental price of land in the suburban zone r_s is exogenous. To compute this parameter, we employ the "Osservatorio del Mercato Immobiliare" (Observatory of the Housing Market) database of housing transactions and rents for the city of Milan, provided by

[34] This database is available at http://dati.comune.milano.it/component/rd/item/27-27-Popolazione-%20residenti%20per%20cittadinanza%20e%20quartiere%20.html. We aggregate the data for different zones as follows. CENTER: "Duomo" "Brera" "Giardini Porta Venezia" "Guastalla" "Vigentina" "Ticinese" "Magenta - S. Vittore" "Parco Sempione" MIDTOWN: "Garibaldi Repubblica" "Centrale" "Isola" "Maciachini - Maggiolina" "Buenos Aires - Venezia" "Loreto" "Città Studi" "Porta Romana" "Navigli" "Ripamonti" "Pagano" "Sarpi" "Farini "Bande Nere" "Lorenteggio" "De Angeli - Monte Rosa" "Washington" "Lodi - Corvetto" "Tibaldi" "Umbria - Molise" "XXII Marzo". SUBURB: all the remainder.

[35] http://dati.comune.milano.it/component/rd/item/364-364%20-%20Censimento%202011-%20Indicatori%20per%20area%20di%20censimento%20ACE.html

the Italian “Agenzia delle Entrate” (Internal Revenue Agency). This database reports monthly average prices for housing transactions in several cities. We extract the average monthly rental price for housing space in the suburban zone of Milan, which was equal to 6.99 €/m^2 in 2007.[36] Because our travel costs are daily, we convert this value in daily terms by using the average number of working days per month in the year 2007, equal to 21. We therefore obtain a rental price of 0.332 € per suburban unit of land per household per working day.

To calibrate the landownership parameters, we refer to census data from ISTAT (2011), reporting that 64% of homes in Milan were owner-occupied in 2011. We take this as a proxy of the share of residential land owned by residents. However, we were unable to find a disaggregate measure for each zone. To account for the fact that resident ownership tends to decrease with distance from the center in most cities, we assume that 33% of residential land in the central island is owned by residents, 50% in the midtown zone and 80% in the suburban zone. We calculate the share of resident-landowner households in each zone by multiplying the baseline quantity of households in each zone provided above by the same percentages. Given the number of households in our baseline scenario (see above), we get a weighted average of 64% of city residential land owned by residents.

[36] Database OMI, year 2007. We take the average rental price for residential buildings, regardless of conservation state. We restrict attention to the following zones: periphery, rural and suburban. This database is available upon request from https://wwwt.agenziaentrate.gov.it/servizi/.