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Second-best urban tolls in a monocentric city with housing market regulations

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ABSTRACT

This paper investigates second-best congestion pricing in a monocentric city characterized by distortionary regulations in the housing market (building height restrictions, no-development areas and property taxation). We demonstrate that the welfare gain of a Pigouvian tax may first fall and then increase as building height restrictions become more stringent. For example, a Pigouvian toll imposed in a city without restrictions may produce up to 40% larger welfare gains than Pigouvian tolling in a city with a mild, uniform in space, floor-to-area ratio restriction. In the presence of a tax-induced distortion, deviations of the Pigouvian toll can lead to non-negligible welfare gains. We discuss the important policy implications of the above findings.

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1. Introduction

Second-best issues are a prominent theme in the contemporary literature on externality regulation. This is true for the transport economics literature in the context of road pricing (Verhoef et al., 1996), the urban economics literature in the discussion on urban growth boundaries (Brueckner, 2007; Anas and Rhee, 2007) and the environmental economics literature, where the double dividend hypothesis is an important theme (e.g. Goulder et al., 1997). Second-best issues may emerge for a variety of reasons. One is that the market for an externality-generating commodity is directly related to the market of another imperfectly priced commodity, because the two commodities are either substitutes or complements. This provides a motive to adjust Pigouvian taxes in the market of primary interest: welfare losses due to deviations of the corrective taxes from marginal external costs are motivated by welfare gains in the related market.

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As an example, in the absence of road pricing, second-best fares in public transportation will reflect unpriced congestion on the road: they will be adjusted downwards (upwards) when public transportation functions as a substitute (complement) to private road use. Similarly, optimal tolls will deviate from their Pigouvian values when traffic-induced externalities in links, routes or entire areas of a network go unpriced. Verhoef (2002a, b) offers a general analytical solution for the second-best problem where not all links of a congested network can be charged; an algorithm based on this analytical solution is then tested on a medium size network. Also, van Dender (2004) shows that constraints in network pricing can cause the optimal toll to deviate from the marginal external cost of congestion in a complex way. These considerations, as well as the corresponding second-best adjustments, vanish once optimal road pricing is implemented.¹

The impact of labor tax distortions on optimal urban road pricing has received considerable attention in the transportation branch of the double-dividend literature. The well-known contribution by Parry and Bento (2001) was the first to examine, in a non-spatial framework, the efficiency of a congestion tax during the peak commuting hours in the presence of a distortionary tax on labor income; Mayeres and Proost (2001) examine the double-dividend in transportation in the presence of heterogeneous agents; van Dender (2003) expanded the analysis by Parry and Bento (2001) to account for traffic that generates externalities but is not subject to a tax-interaction effect; Tikoudis et al. (2015) examined the role of a spatially-varying interaction effect between the labor and road tax, as well as its implications for the design of optimal pricing schemes in a monocentric city; Tikoudis (2018) derived analytical expressions for the traditional double-dividend effects in a polycentric model and showed that, under specific conditions, a Pigouvian tax rule could be welfare-decreasing even if tax revenue is used to reduce the tax on labor income.² The effect of other tax-induced distortions or inefficient pricing mechanisms within the transportation system (e.g. fuel taxes, urban transit subsidies) has also been examined extensively (Parry and Bento, 2002; Parry and Small, 2009).

At the same time, the associated impact of imperfectly functioning land and housing markets on the optimal design of urban road pricing schemes has remained under-researched. In this paper we examine optimal road pricing from that new perspective, i.e. in the presence of various regulations in housing and land markets that are: i) *distortionary*, and thus suboptimal to begin with, and ii) *non-adjustable*, i.e. they are assumed to be fixed, in contrast to road pricing schemes which will be optimized. Both assumptions are relevant for a variety of reasons.

Regarding the first, most urban land and housing markets are heavily distorted due to a range of suboptimal pricing policies (e.g. housing taxation, mortgage interest deduction) and quantity restrictions (e.g. regulated building height, zoning including no-development areas). Empirical observation suggests that quantity restrictions are present in a substantial part of the world. For example, in the Netherlands most municipalities set maximum height restrictions for residential buildings. In most other European countries, similar regulatory restrictions have been implemented.³ Via different channels, housing and land market regulations may cause welfare losses through a suboptimal allocation of space across economic agents and activities, as they are decided in the sphere of politics and do not correspond to a welfare maximization plan.

The second assumption is also reasonable in many respects. Command-and-control regulations might be difficult to adjust when homeowners have strong incentives to lobby for building height restrictions, as well as no-development areas (Fischel, 2001; Schuetz, 2009). That is, quantity restrictions have been shown to increase housing prices in specific contexts (e.g. Ihlanfeldt, 2007) and are, therefore, very likely to remain intact in the years to come. Furthermore, command-and-control restrictions are rigid because of physical reasons, as most of these regulations cannot be adjusted towards certain directions in a formed urban landscape. For instance, once urban fabric has reached the growth boundary of a city, there may be no way to contract that boundary inwards, as that would outlaw existing private property. Similarly, once buildings have been constructed, responses to laxer or tighter building height restrictions are hardly possible, as they imply substantial conversion costs.⁴ Theoretically, property taxes might be less rigid than quantity restrictions. However, housing property taxation has been established as a standard way to raise public revenue.⁵ Furthermore, its adjustment in light of the associated external effects in the transportation sector may be hampered by the lack of coordination between the authority that sets the property tax and the regulator that controls the road charges in an urban area. Most often, these authorities belong to different levels of government and may use these instruments to obtain different objectives.

¹ More recently, the problem of second-best pricing in networks has been examined under the hypothesis of bounded rationality (Di et al., 2013, 2016). Furthermore, a growing literature examines second-best issues resulting from the interactions of independent regulators controlling different parts of a network (see for instance De Borger et al., 2005, 2007; Watling et al., 2015). De Borger and Proost (2012) provide an extensive review of this literature stream.

² Throughout the paper, the terms *Pigouvian (road) toll*, *Pigouvian (road) tax*, *Pigouvian tax rule* and *marginal external cost pricing* are used interchangeably as synonyms, i.e. they all refer to a corrective road tax whose level has been set equal to the marginal external cost of congestion.

³ Building height restrictions are one specific form of land-use planning. Cheshire and Sheppard (2002) find a negative welfare effect of land-use planning in general.

⁴ Even if these regulations were easy to adjust, empirical research suggests that the accompanying land-use changes might not be sufficient to substantially reduce vehicle miles travelled (Heres-Del-Valle and Neiemeier, 2011). For example, Bento et al. (2005) show that the elasticity of vehicle miles travelled with respect to population density is just -0.07 . The effect of city size regulation on travel energy consumption is examined by Larson and Yezer (2015). Vermeulen and van Ommeren (2009) attempt to estimate the effect of regulated housing supply on jobs-housing balance.

⁵ Taxation in the housing market includes transaction as well as property taxes. Taxation may also be negative in case of mortgage interest deduction. Other regulatory channels include rent control (Gyourko and Linneman, 1989,1990; Arnott, 1995) and public housing. See Cheshire and Hilber (2008) for the effect of building height restrictions in the market of office space.

The current paper is closely related to a rapidly developing literature in transport and urban economics that explores the potential of land-use practices to substitute for congestion pricing in the struggle to curb traffic-induced externalities. Looking at the same issue from a diametrically opposite perspective, that stream of research is implicitly motivated by the large implementation costs and the limited political acceptability associated with road pricing. Brueckner (2007) and Anas and Rhee (2007) investigate the efficiency of an urban growth boundary relative to a congestion toll. Optimal floor-to-area ratio (hereafter, FAR) regulations have been examined in conjunction with population externalities by Joshi and Kono (2009) and Kono et al. (2010). More recently, Kono et al. (2012) evaluate the efficiency of building and city size regulations relative to the efficiency of a first-best road toll; Pines and Kono (2012) discuss second-best allocations based on space-varying property taxation and FAR regulations; Kono and Kawaguchi (2017) examine optimal FAR regulation in the presence of second-best road pricing, which takes the form of a cordon toll. The critical differentiator between the above literature and the current paper is that we investigate welfare-enhancing policies exclusively through road pricing, *i.e.* by assuming that housing market regulations are *given* and *rigid*. In a much looser way, this paper is also related to the contribution by Bento et al. (2006), which examines the efficiency and distributional impacts of various anti-sprawl policy instruments, and that by Bento et al. (2011), which is the first study to investigate the interaction between two spatially-uniform taxes on property and developed land, with the latter functioning as an anti-sprawl instrument.⁶

Second-best issues that arise from imperfectly-functioning related markets have different impacts, and therefore different policy implications, depending on the nature of the distortion. It is useful to distinguish between two types of distortions arising from policy interventions: *distortionary taxation* (for example motivated by the need to raise tax revenues) and *quantitative restrictions*. It should be stressed that, throughout the entire paper, it is assumed that these forms of taxation and quantitative restrictions are not justified from a welfare perspective.⁷ From a qualitative viewpoint, the analysis in this paper is relevant whenever taxes or restrictions in the land and housing markets are not set in a welfare-maximizing manner. For expositional convenience, it is assumed that any intervention in these markets would be *per se* welfare decreasing once any other failure, for example traffic externalities, has been removed from the analysis.

In the context of a city where residents commute to a given workplace, we investigate both types of policy interventions—*i.e.*, taxes and quantitative regulations—by focusing on housing taxation and building height restrictions respectively (Arnott and MacKinnon, 1977; Bertaud and Brueckner, 2005). Both interventions have in common that they affect the welfare gains that externality pricing in the primary market of interest (*i.e.* road transport) could bring. But an important difference is that, whereas tax distortions induce deviations from the Pigouvian rule in the primary market (*i.e.* the optimal road tax deviates from the corresponding marginal external cost), any such deviation is not efficiency-enhancing in the case of quantitative restrictions. Therefore, the question of whether externality taxes should be adjusted does not so much depend on whether there are distortions in the related markets, but much more on the type of these distortions.⁸

While the optimality of a marginal external cost pricing rule is retained in the presence of a quantity restriction, the optimal level of the associated tax depends heavily on the stringency of that quantity regulation. For instance, when inefficiently tight environmental standards for vehicles are present, the marginal external cost of vehicle use is inefficiently low, thus the Pigouvian level of the associated externality tax is low (and *vice versa*). In the context of this paper, tighter building height restrictions increase the traffic volume and thus the traffic-induced externalities everywhere within a monocentric city, calling for higher levels of road taxes, but not for a change of the Pigouvian tax rule. However, the magnitude of the background quantitative restriction remains important, not only because it determines the level of the optimal externality tax, but also the welfare gains that the tax could yield. In the specific context of the study, it is examined how the stringency of land-use regulations (building height limits, no-development areas) determines the size of the welfare gains from a Pigouvian toll. Among other things, this analysis indicates the extent to which the gains from congestion charges for cities without any regulations in land and housing markets can be extrapolated to cities where such regulations are strict (and *vice versa*).

We use as a starting point the voluminous literature on the welfare costs of land-use and housing market regulations (Brueckner, 1996; Bertaud and Renaud, 1997; Bertaud and Brueckner, 2005; Glaeser et al., 2005; Cheshire and Hilber, 2008).⁹ In the current paper, a monocentric city framework is expanded to incorporate congestion as in Verhoef (2005) and, more recently, Tikoudis et al. (2015). The paper considers a *space-varying* road tax, which has the merit of capturing the spatial

⁶ Bento et al. (2006) examine the efficiency and distributional impacts of urban growth boundary and taxes on property, developed land and gasoline. Development taxes and urban growth boundaries are found to be the most efficient anti-sprawl instruments. The paper highlights how the optimal choice of instrument depends on whether the distributional impacts are taken into account. Bento et al. (2011) shows that these taxes may interact negatively (*i.e.* the development tax erodes the base of the property tax by preventing development at the city fringe), but may also interact positively, because the development tax leads to a more compact city with relatively larger open spaces, which are more accessible from anywhere within a monocentric city. Then, house prices rise everywhere, implying a positive effect of the development tax on the property tax base.

⁷ Given optimal road pricing and provided land and housing markets function efficiently, there is no societal benefit from complementing road pricing with land use policies when transport externalities are the only market failure (Verhoef, 2000). Benefits may arise when road pricing fails to internalize traffic induced externalities.

⁸ See, for instance, Larsen et al. (2008), who show that the calculation of the optimal road tax for commuters depends on the presence of a distortionary tax on moving residence, but does not depend on restrictions that hamper the relocation of commuters.

⁹ In Bertaud and Brueckner (2005), the welfare cost from a certain level of building height restrictions in a monocentric city is shown to be equal to the difference in commuting costs that the household in the city fringe would face if the building height restrictions were removed. Numerical simulations suggest the welfare cost to be 2% of household income. For an empirical application for India, see Brueckner and Shridhar (2012).

variation of externalities, as well as the variation of tax interaction effects across space. However, the continuous-space variation prevents the derivation of analytic expressions for the traditional double dividend effects, for example similar to those derived in Bento et al. (2011), where space is continuous but the corrective tax is space-uniform, or in Tikoudis (2018), where the corrective tax varies across the links of a congested network. The numerical version of the model is calibrated so that the benchmark equilibrium reproduces a set of stylized facts characterizing a highly representative monocentric city in absence of congestion charges.

Our results confirm that when there are only quantitative distortions in the housing market, the Pigouvian tax rule remains optimal independent of their magnitude. Using the parameters of the benchmark equilibrium, we compute the welfare effect of the Pigouvian toll as a function of the maximum FAR allowed. It is shown that this effect is not only sensitive to the presence of building height restrictions, but also *non-monotonic*. That is, a Pigouvian toll imposed in a city with a mild FAR restriction may yield up to 40% smaller welfare gains than those generated by the same tax rule (*i.e.* marginal external cost pricing) in a city without building height restrictions. At the same time, the welfare gains recorded in the former case, *i.e.* in a city with a mild FAR restriction, turn out to be smaller than those realized in a city where the regulation is very stringent. The result highlights that the welfare gains from an identical externality tax rule can be identical even when the associated levels of the externality tax differ widely. In turn, this implies that extrapolating the welfare gains (from contexts where road pricing has already been implemented) to urban environments that share similar road technology and economic conditions may result in substantial inaccuracies, even if the cities have been developed in relatively similar ways. Finally, it is demonstrated that in the presence of a housing property tax the Pigouvian tax rule is not the optimal recipe to curb road traffic externalities. It is shown that the level of the property tax determines the degree to which the optimal road taxes deviate from their Pigouvian levels and the additional welfare gains that the deviation could bring. These gains are not negligible, but they turn out to be much smaller than those recorded in the corresponding case in which the road tax interacts with a labor tax (Tikoudis et al., 2015), since the latter interaction is much stronger.

The structure of the paper is as follows. Section 2 introduces the analytical model. Section 3 presents the numerical calibration and the stylized facts that characterize the benchmark equilibrium (in absence of housing market regulations). Section 4.1 discusses the welfare effects of the Pigouvian toll at various levels of a uniform FAR restriction. Section 4.2 shows the respective results for the case of no-development areas. Section 4.3 presents numerical results for the case of a distortionary housing property tax. Section 5 summarizes and concludes.

2. Model

The analytical model presented in this section extends the models used in Verhoef (2005) and Tikoudis et al. (2015), using elements from Bertaud and Brueckner (2005) and Muth (1969).¹⁰

2.1. Households

Households are located anywhere within a linear monocentric city, *i.e.* a city with a single spaceless central business district (hereafter, CBD) where all jobs are located. Let z and $\bar{z}$ denote the distances of an arbitrary household and the city fringe, respectively, from the CBD. Utility is derived from the consumption of a numéraire good, y ; floor space, s ; and leisure time, ℓ . Assuming Constant Elasticity of Substitution (CES) preferences, the household that locates at distance z from CBD maximizes:

$$U_z = \left[(\alpha y_z)^\rho + (\beta s_z)^\rho + (\gamma \ell_z)^\rho \right]^{\frac{1}{\rho}}, \quad (1)$$

where the elasticity of substitution between consumption, space and leisure is determined via $\sigma = 1/(1 - \rho)$ and α , β and γ are parameters.¹¹ The total time endowment, T (*e.g.* a year), is spent on commuting, working, and leisure. The within-day labor supply is inelastic, thus the working day is of fixed duration, $\bar{t}_L$. Every trip to work requires t_z units of time. For L_z working days the time constraint becomes:

$$T = L_z t_z + L_z \bar{t}_L + \ell_z. \quad (2)$$

Normalizing the duration of the working day, $\bar{t}_L$, to one, the time constraint becomes:

$$T = L_z (1 + t_z) + \ell_z \Leftrightarrow L_z = (T - \ell_z) / (1 + t_z). \quad (3)$$

The budget constraint is:

$$\underbrace{p_y y_z + p_z (1 + \tau_V) s_z}_{\text{housing expenditure}} = B + L_z \underbrace{(w - \tau_z - mz)}_{\text{net daily wage}} \quad (4)$$

¹⁰ The exposition in Section 2 draws heavily from these two contributions. Literal citations from these sources are not marked as such for reasons of legibility. Identical equations are included here to keep this paper self-contained.

¹¹ It holds that $\lim_{\rho \rightarrow 1} \sigma = \infty$ for the three arguments being perfect substitutes; $\lim_{\rho \rightarrow -\infty} \sigma = 0$ for the arguments being perfect complements and $\lim_{\rho \rightarrow 0} \sigma = 1$ for the case of Cobb-Douglas preferences.

where B denotes a lump-sum transfer (discussed below) from the government to the household, independent of its location; the net daily wage is defined as the difference between the gross daily wage, w , and the total pecuniary commuting cost. The latter consists of the total road toll charged between z and the CBD, τ_z , and the operational cost (gasoline, vehicle depreciation *etc.*), mz , which we assume is a linear function of the commuting distance. In the left hand side of (4), p_y denotes the normalized price of composite consumption (*i.e.* the price of numéraire); p_z denotes the price of residential floor space at location z ; and τ_v denotes the *ad valorem* property tax rate (if imposed). Inserting (3) into the right hand side of (4) yields the combined constraint:

$$B + \underbrace{\left(\frac{w - \tau_z - mz}{1 + t_z} \right)}_{\text{shadow value of time } (v_z)} (T - \ell_z) = p_y y_z + p_z (1 + \tau_v) s_z, \quad (5)$$

where the fraction in the left hand side of (5) represents the shadow value of time at location z , denoted hereafter by v_z . Rearranging (5) yields:

$$\underbrace{B + v_z T}_{\text{full income } (M_z)} = p_y y_z + p_z (1 + \tau_v) s_z + v_z \ell_z \quad (6)$$

where the left hand side of (6) is the full income of the household at distance z , M_z , *i.e.* the maximum income that can be realized when leisure time is set to zero. Full income can be used to buy back leisure at its shadow value, v_z , generic consumption and residential space. Maximizing (1) subject to (5) and defining $\chi = \rho/(\rho - 1)$ yields the conditional (on z) Marshallian demand functions for the composite good, space and leisure time respectively:¹²

$$y_z^* = M_z \frac{(p_y/\alpha^\rho)^{-\sigma}}{\left(\frac{p_y}{\alpha}\right)^\chi + \left(\frac{p_z(1+\tau_v)}{\beta}\right)^\chi + \left(\frac{v_z}{\gamma}\right)^\chi}, \quad (7)$$

$$s_z^* = M_z \frac{(p_z(1+\tau_v)/\beta^\rho)^{-\sigma}}{\left(\frac{p_y}{\alpha}\right)^\chi + \left(\frac{p_z(1+\tau_v)}{\beta}\right)^\chi + \left(\frac{v_z}{\gamma}\right)^\chi}, \quad (8)$$

$$\ell_z^* = M_z \frac{(v_z/\gamma^\rho)^{-\sigma}}{\left(\frac{p_y}{\alpha}\right)^\chi + \left(\frac{p_z(1+\tau_v)}{\beta}\right)^\chi + \left(\frac{v_z}{\gamma}\right)^\chi}. \quad (9)$$

Finally, substituting (7)–(9) into the objective function yields the conditional indirect utility:

$$V_z^* = M_z \left\{ \left(\frac{p_y}{\alpha}\right)^\chi + \left(\frac{p_z(1+\tau_v)}{\beta}\right)^\chi + \left(\frac{v_z}{\gamma}\right)^\chi \right\}^{-1/\chi}. \quad (10)$$

The spatial equilibrium is characterized by locational indifference, *i.e.* constant utility across space. Eq. (10) can then be reformulated to express the price of floor space as a function of equilibrium utility:

$$p_z(u) = \frac{\beta}{(1 + \tau_v)} \left\{ \left(\frac{M_z}{u}\right)^\chi - \left(\frac{p_y}{\alpha}\right)^\chi - \left(\frac{v_z}{\gamma}\right)^\chi \right\}^{1/\chi}. \quad (11)$$

Now, Eq. (11) can be plugged into (7), (8) and (9) to yield the compensated demands for the composite good, space and leisure at any arbitrary distance z , which are denoted by $y_z(u)$, $s_z(u)$, and $\ell_z(u)$ respectively.

2.2. Developers

Competitive developers use constant returns to scale technology to convert land and capital into residential space. The capital intensive form of the Cobb–Douglas production function for residential space per unit of land (hereafter, FAR) is:

$$\hat{s}_z = g \hat{k}_z^\delta, \quad (12)$$

where $\hat{s}$ denotes the residential floor space per unit of land. The corresponding profit per unit of land is:¹³

$$\pi = p_z g \hat{k}_z^\delta - R \hat{k}_z - r_z, \quad (13)$$

¹² Inserting (9) into (3) and solving yields the endogenous number of working days.

¹³ The capital intensive form of the production function in Eq. (12) can be derived from a standard Cobb–Douglas production function with constant returns to scale, by dividing both sides by the land input. Similarly, the profit per unit of land is derived by dividing the standard profit function of the developer by the amount of land input.

where $g > 0$ is a technology constant, $\hat{k}$ denotes the units of capital per unit of land (hereafter, *structural density*), R the exogenous price of capital and r_z the per-unit price of land at z .¹⁴ A “hat” thus denotes variables expressed on a per-unit-of-land basis. Dividing the supplied space in (12) by the compensated space demand per household at distance z , s_z , yields the *household density* at point z :

$$n_z = \frac{g\hat{k}_z^\delta}{s_z}. \quad (14)$$

From the first-order condition for profit maximization, we derive the (privately) optimal structural density:

$$\hat{k}^* = \left(\frac{R}{\delta p_z g} \right)^{1/(\delta-1)}. \quad (15)$$

Inserting (15) into (13) and solving for zero profits, yields the land rent:

$$r_z = (1 - \delta) \left(\frac{R}{\delta} \right)^{\delta/(\delta-1)} (p_z g)^{1/(1-\delta)}. \quad (16)$$

2.3. Firms

A representative competitive firm, which is located at the CBD, operates under constant returns to scale, producing the composite good with capital and labor according to a Cobb–Douglas technology:

$$Y = K^\zeta L^{1-\zeta}. \quad (17)$$

From cost minimization we derive the *conditional factor demands* for labor:

$$L^D = Y \left(\frac{(1 - \zeta)R}{\zeta w} \right)^\zeta, \quad (18)$$

and capital:

$$K_Y^D = Y \left(\frac{\zeta w}{(1 - \zeta)R} \right)^{1-\zeta}. \quad (19)$$

Using (18) and (19), it can be shown that the marginal cost of the composite good is:

$$R^\zeta w^{1-\zeta} \left[(1 - \zeta)^{\zeta/(1-\zeta)} + \zeta^{(1-\zeta)/\zeta} \right]. \quad (20)$$

2.4. Commuting

Commuting trips from any given location z to the CBD are made along a single road, used by all households. We specify the travel time per unit of distance at location z as a linear function of aggregate traffic flow at that location:

$$t_0 + t_1 \underbrace{\left(\int_z^{\bar{z}} n_\psi L_\psi d\psi \right)}_{\text{aggregate flow at location } z} \quad (21)$$

i.e. the sum of the free-flow travel time per unit of distance, t_0 , and a term that represents the congestion delay caused by the aggregate traffic flow at z .¹⁵ That flow, represented by the integral in (21), contains all commuting trips by households located between z and the city limit, $\bar{z}$. Multiplying the aggregate flow with a sensitivity parameter, t_1 , yields the time delay per unit of distance at each point z .¹⁶ Integrating (21) over the interval $(0, z)$ yields the commuting time for the household at z :¹⁷

$$t_z = z t_0 + t_1 \int_0^z \min\{z, \psi\} n_\psi L_\psi d\psi. \quad (22)$$

¹⁴ Besides the distortions that are specified explicitly in the paper and are *policy-induced* (i.e. taxes, regulations) the housing and land markets are assumed to operate efficiently. Note that the framework developed in this paper can be used to study how *market-induced* inefficiencies in pricing (e.g. market power that leads to a deviation between marginal social costs and benefits) would affect road pricing policies.

¹⁵ Therefore, the essence of congestion is captured by assuming that the travel time per unit of distance increases with the number of vehicles passing that point; the linear form is chosen for analytical convenience.

¹⁶ There is no time variation in traffic levels and speeds, i.e. we use a static, time-averaged representation of commuting. Every working day is identical; thus, the daily traffic flow on any location is the yearly flow, divided by a constant (the total number of working days). This constant is, in turn, fully reflected in the slope of the congestion function, i.e. in the value of t_1 .

¹⁷ Note that in (21), z refers to a location along the road and ψ to household locations, while in (22) and (23) it is z that refers to household location.

An additional commuting trip generated by a household at distance z increases the travel time of a commuter located at $\psi \geq z$ by $t_1 z$, and the travel time of a commuter located at $\psi \leq z$ by $t_1 \psi$. Multiplying this delay with the *shadow value of time* at ψ , $(w - \tau_\psi - m\psi)/(1 + t_\psi)$, and labor supply at ψ , $n_\psi L_\psi$, provides a measure for the marginal external cost of an additional unit of labor imposed by the commuter at z to the commuter at ψ .¹⁸ Integrating over the interval $(0, \bar{z})$ thus yields the *marginal external cost of congestion* generated by the household located at z :

$$\text{mecc}(z) = t_1 \int_0^{\bar{z}} \min\{z, \psi\} n_\psi L_\psi \left(\frac{w - \tau_\psi - m\psi}{1 + t_\psi} \right) d\psi. \quad (23)$$

2.5. Government and public budget

The government can tax (or subsidize) road use, and recycles the tax revenue in a manner that ensures a balanced budget. Furthermore, we assume that excess land rents (*i.e.* exceeding the agricultural land rent level) remain in the city. We model that as if the government collects these excess land-rents and redistributes them in a lump-sum manner. In particular, the total land revenue collected is the sum:

$$G_L = G_a + G_e = \bar{z} r_A + \underbrace{\int_0^{\bar{z}} (r_z - r_A) dz}_{\text{excess land rent}} \quad (24)$$

The first term, $G_a = \bar{z} r_A$ (where r_A refers to the agricultural rent), is transferred to an absentee land owner. The second term, G_e , *i.e.* the excess land rent (the expenditure that exceeds the opportunity cost of land), is returned to the consumers in a lump-sum manner.¹⁹ This assumption on rent recycling ensures that the city cannot expand without cost while the excess rents remain within the urban economy.²⁰

When imposed, a location-based road tax generates the revenue:

$$G_R = \int_0^{\bar{z}} n_z L_z \tau_z dz, \quad (25)$$

which is endogenous, since it depends on density, n_z , labor supply, L_z , and city size, $\bar{z}$. The road toll, τ_z , gives the total trip toll for a resident living at z , and hence it is not a local toll for passing location z . Furthermore, the revenue from the *ad-valorem* tax on property is:

$$G_P = \tau_V \int_0^{\bar{z}} p_z g k_z^\delta dz. \quad (26)$$

Toll and tax revenues are returned in the form of a lump-sum transfer. Therefore, the lump-sum transfer per household, B (see Eq. (5)), can be written as:

$$B = \frac{G}{N} = \frac{G_e + G_R + G_P}{N}, \quad (27)$$

where G denotes the total recycled revenue.

2.6. Equilibrium without distortions in the housing markets

In equilibrium, the (closed) city must accommodate the exogenous population, N , thus:

$$\int_0^{\bar{z}} n_z dz = N. \quad (28)$$

All land between the CBD and the fringe $\bar{z}$ is acquired from an absentee landlord at its exogenous opportunity cost, *i.e.* the agricultural rent (r_A). Thus, the city fringe, $\bar{z}$, is endogenously determined via the condition:

$$r_A = R^{\delta/(\delta-1)} (p_z g)^{1/(1-\delta)} (\delta^{\delta/(1-\delta)} - \delta^{1/(1-\delta)}), \quad (29)$$

¹⁸ The volume delay function is the same as the one used in Verhoef (2005) and is in line with those used in other monocentric city models, for instance by Mun et al. (2003) and Brueckner (2007). None of the results depends on the fact that the congestion function is linear. In a non-linear variation, formula (23) would change accordingly, but all findings would remain intact from a qualitative viewpoint.

¹⁹ In that sense, the model follows closely the specification of the *closed-city under public ownership* model proposed in Fujita (1989).

²⁰ This holds because the absentee landlord concedes the land for development at its opportunity cost, which is the return from an alternative use (in this case agriculture). If the absentee landlord assumption is dropped, it is then implicitly assumed that *all* land (*i.e.* also the land beyond the city fringe) is owned by the city's population. The city in that case expands without cost, as all land expenditure returns to that population. It is therefore much larger, extending up to the location at which bid rent equals zero.

where the right hand side gives the equilibrium value of (16) evaluated at $\bar{z}$. The rest of the equations comprise the clearing of the labor market:

$$\underbrace{\int_0^{\bar{z}} \left(\frac{T - \ell_z}{1 + t_z} \right) n_z dz}_{\text{aggregate labor supply}} = Y \underbrace{\left(\frac{(1 - \zeta)R}{\zeta w} \right)^\zeta}_{\text{labor demand}} \quad (30)$$

the zero profit condition for the representative firm:

$$\underbrace{R^\zeta w^{1-\zeta} \left((1 - \zeta)^{\zeta/(1-\zeta)} + \zeta^{(1-\zeta)/\zeta} \right)}_{\text{marginal cost of numéraire}} = p_y \quad (31)$$

which is obtained by setting the normalized price of the numéraire equal to the marginal cost of the composite good and the closing identity:

$$\underbrace{p_y \left(Y - \int_0^{\bar{z}} y_z n_z dz \right)}_{\text{value of exports}} = \underbrace{\bar{z} r_A + R \left(Y \left(\frac{\zeta w}{(1 - \zeta)R} \right)^{1-\zeta} + \int_0^{\bar{z}} \left(\frac{R}{\delta p_z g} \right)^{1/(\delta-1)} dz \right)}_{\text{value of imported capital}} + \underbrace{m \int_0^{\bar{z}} n_z D_z dz}_{\text{value of commuting expenditure}} \quad (32)$$

which requires the value of the city exports (left-hand side) to be equal to the opportunity cost of land, $\bar{z} r_A$, the value of imported capital and the pecuniary expenditure used for commuting. The value of imported capital, i.e. the second term in the right hand side of (32), is the product of its exogenous price, R , and the sum of: i) the demanded quantity by the representative firm, given by Eq. (19), and ii) the demanded quantity by the construction sector developers, i.e. the integral of (15) across space. The pecuniary expenditure used for commuting, i.e. the final term in the right hand side of (32), is the product of the kilometer cost, m , and the total distance traversed by all commuters in the city.

Eqs. (28)–(31) define a non-linear system in four unknowns: Y , $\bar{z}$, w , u . The remaining endogenous variables (M , y , s , L , ℓ , p , r , $\hat{s}$, n , G_L , G_a , G_e , G_R , G_p , G , B , t , $\hat{k}$, v , V , L^D , K_P^D , $mecc$), and where relevant their spatial patterns, are determined by the values of the above four variables, through the equations in Sections 2.1–2.5. The interested reader is referred to Appendix B for the details of the solution algorithm.

2.7. Equilibrium with a uniform building height restriction

In this paper, we consider the case of a uniform floor-to-area ratio (FAR) restriction as a distortionary quantity restriction in the housing market. The restriction is uniform in the sense that it applies across the entire city, i.e. throughout the interval $[0, \bar{z}]$. However, because in a standard monocentric city model structural density falls with distance from CBD, the constraint may not be binding at some, more remote locations in the interior of the city. This introduces a new endogenous variable, which is the distance from CBD at which the maximum height constraint ceases to be binding. Hereafter, that variable is referred to as the *building height restriction boundary* (or *BHR boundary*) and is denoted by $\hat{z} \in [0, \bar{z}]$. Eq. (12) becomes:

$$\hat{s}_z = \begin{cases} \bar{h} & \text{if } z < \hat{z} \\ g \hat{k}_z^\delta & \text{if } z > \hat{z} \end{cases} \quad (33)$$

where $\bar{h}$ is the maximum number of floors (floor-to-area ratio) permitted at any point in the city. The equilibrium population density in (14) becomes:

$$n_z = \begin{cases} \frac{\bar{h}}{s_z} & \text{if } z < \hat{z} \\ \frac{g \hat{k}_z^\delta}{s_z} & \text{if } z > \hat{z} \end{cases} \quad (34)$$

The equilibrium condition in (28) is now written as:

$$\left[\int_0^{\hat{z}} \frac{\bar{h}}{s_z} dz + \int_{\hat{z}}^{\bar{z}} \frac{g \hat{k}_z^\delta}{s_z} dz \right] = N. \quad (35)$$

The additional endogenous variable, $\hat{z}$, is accompanied by a new equation in order for the model to close. This states that the building height at point $\hat{z}$ is equal to the restricted height limit, $\bar{h}$. Inserting (15) into (12), this condition can be written as:

$$\hat{s}_{\hat{z}} = g \left(\frac{R}{\delta p_{\hat{z}} g} \right)^{\delta/(\delta-1)} = \bar{h}. \quad (36)$$

2.8. Equilibrium with no-development areas

The other quantity restriction examined in this paper is no-development areas. Given no-development areas, the structural density, $\hat{k}$, and floor-to-area ratio, $\hat{s}$, are restricted to be zero in an interval (z_L, z_U) specified by government. That is:

$$\hat{s}_z = \begin{cases} gk_z^\delta & \text{if } z < z_L \text{ or } z > z_U \\ 0 & \text{if } z_L \leq z \leq z_U. \end{cases} \quad (37)$$

Furthermore, travel times in (22) and marginal external costs in (23) are adjusted for the fact that the flow at any point in the interval (z_L, z_U) remains constant. As in the unregulated case, the rent at the city fringe is given by Eq. (29); no specific restrictions apply to points z_L and z_U . Despite the fact that zoned land is required to be vacant, it is still acquired from the absentee landlord at the opportunity cost of land.

2.9. Optimal road tax policies

In the current paper, as discussed in the introduction, we do not formally derive the optimal road tax policies (as well as the welfare changes because of deviations of the optimal tax) as the focus will be on numerical calibration and simulation. It is well known, however, that if no other market than the road market is distorted, then the optimal road toll is equal to the marginal external costs of road use, in line with Pigou (e.g., Verhoef, 2000; Small and Verhoef, 2007). This result also holds in our model (a sketch of the proof can be received upon request). Hence, also for the model sketched above, the Pigouvian road toll formula is the optimal one when there are no further market failures in the urban economy. This result also holds in the case of binding quantity restrictions in the housing market (again, a sketch of this proof can be received upon request). This latter result is also intuitive, as a binding quantity restriction in the housing market would make agents unresponsive to marginal deviations from the Pigouvian road tax. Stated differently, such deviations would lead to welfare losses in the transport market without bringing benefits in the housing market. A similar reasoning does not apply in the case of distortionary taxation in the housing market. Since marginal social benefits do not equal marginal costs in that market, a deviation from Pigouvian taxes in the road market could yield welfare gains or losses in the housing market if it affects housing quantity decisions. The resulting second-best tax does not have a convenient closed-form expression like the Pigouvian toll in (23), and will be approximated numerically. We refer to that numerical approximation as the *optimal tax interpolant* in the examples that follow.

3. Numerical calibration and simulation

3.1. Unregulated equilibrium

We now turn to the numerical version of the model presented in Section 2. The calibration of the unregulated equilibrium (hereafter, the *free market* equilibrium) is in line with Tikoudis et al. (2015). We set the parameters such that the equilibrium characterizes a plausible congested metropolitan area in absence of congestion policies, see Table 1. In equilibrium, the distance between the CBD and the city fringe (40 km) is covered in 54 minutes. The average speed ranges between 14 and 44 Km/h depending on the location from which the commuter departs. The speed of the household located halfway between the CBD and the city fringe is approximately 32 Km/h, which is roughly consistent with the average commuting speed reported for large US cities in the national household travel survey. The speed near the CBD is one-fifth of the speed in the city fringe. The floor-to-area ratio ranges between 25.0 (CBD) and 0.2 floors (fringe). Housing prices in the CBD are roughly 3.5 times those in the fringe. This price variation is accompanied by a respective variation in residential size (2.5 times larger in the fringe) and a steeper variation in land prices and structural density.

Households work between 290 (CBD) and 233 (fringe) days per year (we assume the maximum would have been 365 days, so we ignore compulsory weekends and bank holidays). The (endogenous) annual income of the representative household is approximately € 43,000, almost all of which (92.4%) is earned by labor. This house income is spent on consumption (57%), housing (39%) and transport (4%). The maximum marginal external congestion cost, i.e. as generated by the most remote household, is roughly € 4000, approximately € 17 per working day and slightly above 9% of the mean income. The solid lines in Fig. 1 show the spatial patterns of some of the key endogenous variables of interest.

3.2. Pigouvian toll

The dashed lines in Fig. 1 indicate how the key variables of interest are affected (in the long-run) when a road charge equal to the marginal external cost of congestion, i.e. the scheme in (23), is imposed throughout the metropolitan area in the otherwise optimal situation where no constraints apply.

Clearly, floor-to-area ratio adjusts upwards in locations fairly close to the CBD and downwards in locations further away. Accompanied by a similar adjustment in prices, this reflects changes in relative accessibility occurring after the introduction of the policy. The small elasticity of labor supply with respect to pecuniary commuting costs underlies negligible adjustments in labor supply. In contrast, with adjustments through the behavioral margin of relocation, significant changes take

Table 1
Benchmark equilibrium.

Variable	Value
Expenditure shares	
Consumption share of income	0.566
Housing expenditure share of income	0.390
Transportation expenditure share of income	0.044
Labor supply and commuting	
Labor supply (in days) ^a	272.44
Labor income (in €) (% of total income)	39,932 (92.34%)
One-way commuting time, fringe (in minutes) (resp. average speed) ^b	54.24 (44.24 km/h)
One-way commuting time, halfway (in minutes) (resp. average speed) ^b	37.07 (32.37 km/h)
Speed at fringe to speed at CBD ratio	5.478
Free flow to equilibrium speed ratio	3.068
Average one way commuting time (minutes) ^b	15.68
Average one way commuting distance (km)	6.495
Value of time (as a fraction of wage)	0.896
Income from rents (in €)(% of total income)	3311 (7.66%)
Free-flow commuting speed	74.83 km/h
Distances	
CBD-to-fringe distance (km)	40.0

^a Assuming a year of 365 days. The number could drastically change if the total number of days is adjusted for holiday allowances and weekends. For instance, with weekends excluded and with an annual leave allowance of twenty days, the average supply falls to 179.7 days.

^b Assuming that the exogenous duration of the working days, that was normalized to one in Eq. (3) is 8.0 hours (since t_z is measured in the same unit as the within-day labor supply).

Fig. 1. Equilibria without building height regulations.

Notes: Solid curves: unregulated equilibrium; dashed curves: Pigouvian equilibrium; upper left panel: floor-to-area ratio (FAR); upper right panel: commuting time; lower left panel: residential space prices; lower right panel: marginal external congestion cost.

place in commuting times and speeds. The reduction in the total external costs in the model is associated with a welfare gain; the compensating variation from the Pigouvian toll is approximately € 66 per household, annually. The next section investigates the performance of the Pigouvian toll and other policies in a city where the floor-to-area ratio is regulated.

Fig. 2. Cities with various FAR stringency levels in absence of road pricing.

Notes: Upper left panel: floor-to-area ratio (FAR); upper right panel: commuting times; lower left panel: population densities; lower right panel: marginal external congestion costs.

4. Policy analysis

4.1. Pigouvian toll in cities with different maximum FAR

A natural question arising in the context of this paper regards the extent to which welfare gains of the Pigouvian toll vary across different levels of preexisting building height regulations. The left panel of Fig. 2 illustrates the population density in a series of cities emerging from the same parameters used in the benchmark equilibrium of Section 4.1, but under various maximum floor-to-area ratios imposed by the planning authorities.²¹ The associated values of the *BHR* boundary ($\hat{z}$) and city size ($\bar{z}$), before ($\hat{z}_0$ and $\bar{z}_0$) and after ($\hat{z}_1$ and $\bar{z}_1$) the introduction of Pigouvian toll are given in Table 2. The values of column $\bar{z}_0$ confirm that city size increases as the FAR restriction becomes more severe.

The total welfare gain of the Pigouvian toll in this series of cities can be conceptually decomposed into two separate effects. The first regards the *direct benefits* realized on the transport market. When labor supply responds mildly to commuting distance, vehicle kilometers are expected to increase with city size. Cities with a lower maximum FAR produce more vehicle kilometers, longer commuting times and larger total external costs, as suggested by the upper right and lower right panels of Fig. 2. Thus, the Pigouvian toll in these cities will produce a larger direct benefit (on the road).

The second effect regards *indirect benefits or losses* realized in the housing market. In particular, the road toll scheme may increase the effective demand for floor space in locations where the maximum FAR restriction is already binding, and

²¹ The maximum FAR values are chosen arbitrarily.

Table 2
Pigouvian toll in cities with different FAR regulations.

Road toll scheme	Relative efficiency	$\bar{z}_0$	$\bar{z}_1$	$\hat{z}_0$	$\hat{z}_1$
Maximum FAR allowed					
Free ^a	1.000	40.0	37.8	–	–
20.0	0.741	40.1	38.3	0.95	1.7
15.0	0.587	40.8	39.3	2.8	3.3
10.0	0.640	42.9	41.7	6.6	6.8
6.00	0.884	47.6	46.4	14.0	13.5
4.00	1.060	53.0	51.8	22.3	21.0

^a The resulting floor-to-area ratio in the CBD of the free market equilibrium is approximately 24.5; $\bar{z}$ and $\hat{z}$ denote city size and BHR boundary respectively, before $(\bar{z}_0, \hat{z}_0)$ and after $(\bar{z}_1, \hat{z}_1)$ the introduction of a Pigouvian toll. The welfare gains (compensating variations) of a Pigouvian toll in a city with an arbitrary maximum building height are expressed relative to the respective gains in the city without building height restrictions.

in locations where FAR is close to its maximum level imposed by the regulator.²² Thus, Pigouvian toll may expand the *BHR* boundary of the city and cause welfare losses in the housing market.

Table 2 suggests that this may be the case for cities with a mild FAR restriction, lying not far below the respective FAR of the free-market equilibrium. The rationale behind this counter-intuitive result is that the population residing in the close neighborhood of *BHR* boundary, i.e. the population density contained on an interval $(\hat{z}_0, \hat{z}_0 + \Delta\hat{z}_0)$, is larger in these cities (see lower left panel of Fig. 2). Consequently, a larger such population (prior to the Pigouvian toll) will generate a larger expansion of the *BHR* boundary (after the introduction of the Pigouvian toll). This expansion is given by the difference $\hat{z}_1 - \hat{z}_0$ in Table 2, and becomes smaller as the *BHR* regulation becomes more stringent and as the pre-toll *BHR* boundary, $\hat{z}_0$, moves further away from the CBD. The results in the same table suggest that, in cities where FAR lies far below its free market equilibrium level, a Pigouvian toll can even contract the *BHR* boundary. In this numerical example that holds, roughly, when maximum FAR falls below 8.00. In that case, the overall contractive effect of the Pigouvian pricing rule outweighs the aforementioned centrifugal effect it exerts on the *BHR* boundary. The latter effect becomes very weak, since at the *BHR* boundary the population density is relatively lower, while commuting costs and the level of the Pigouvian toll are relatively higher.

Combining the effects on the road and the housing market yields the total welfare gain induced by a Pigouvian toll in a city with a maximum FAR. Table 2 (second column) reports this gain relative to the welfare gain in a city without building height restrictions.²³ This relative gain turns out to be non-monotonic across cities with different maximum FAR. It is the outcome of two functions: a road market benefit function (increasing in regulation stringency) and a housing market loss function (decreasing in regulation stringency). It is also volatile enough to fall below 60% (that is, 59% in the case of fifteen floors).

The above findings have significant policy implications. They indicate that the same policy rule in a series of seemingly identical cities (in terms of road technology, preferences, structure, size, and population) can generate rather diverse welfare effects. Improvised extrapolations of benefits across such cities may lose the point, and thus should not constitute the basis for decision making if not accompanied by elaborate cost–benefit analyses. The latter do not require background information on building height restrictions, as long as traffic forecasts and in particular marginal external cost estimates are consistent with these restrictions.

4.2. Pigouvian toll in a city with no-development areas

Similar to a maximum FAR, a no-development area constitutes a quantity distortion. More specifically, it can be seen as a special case of a building height restriction, in which FAR is forced to be zero in a specified area, for example an interval (z_L, z_U) . For this reason, the Pigouvian toll is optimal, as it is the case with a uniform maximum FAR. In contrast to a uniform maximum FAR, however, the extent of the distortion in the housing market remains unaffected after the introduction of a Pigouvian toll. That is, the area where the restriction applies remains intact. As a result, road externalities determine completely the extent of welfare gains in any arbitrary choice of no-development area (z_L, z_U) .

When the lower bound, z_L , is placed close to the CBD, expanding the no-development area forces households to relocate further away. With mild adjustments in labor supply, total external costs of congestion rise. Then, the Pigouvian toll produces gradually larger welfare gains as the extent of the vacant area increases (first row of Table 3). The opposite is true when the bound is placed relatively close to city fringe. In this case, extension of the no-development area causes relocation closer

²² Note that, in contrast to Section 3, here we are not referring to a marginal adjustment of an existing toll scheme, but to the introduction of a toll scheme equal to the marginal external cost of congestion.

²³ For instance, letting CV_s denote the compensating variation of the Pigouvian toll in a city where maximum FAR is restricted to be equal to s (both before and after the introduction of the policy), and CV_{free} the associated compensating variation in a city without a maximum FAR (either before or after the introduction of the policy), the relative efficiency is $RE_s = CV_s/CV_{free}$.

Table 3
Pigouvian toll in cities with a no-development area.

Extent of no-development area (km)	1.00	2.00	3.00	4.00
Lower bound (km from CBD)				
0.40	1.134	1.338	1.597	1.870
4.00	1.021	1.023	0.998	0.954
30.00	0.995	0.992	0.989	0.986

Notes: All welfare gains are expressed in terms of compensating variations relative to the case without no-development areas.

Table 4
Pigouvian and optimal toll in cities with a different ad-valorem tax on housing property.

Road toll scheme	Pigouvian toll	Optimal tax interpolant	% change in welfare gains	% change in city size
Value tax rate				
0%	1.0	1.0	0%	0%
4%	1.021	1.028	0.7%	−0.87%
6%	1.030	1.059	2.8%	−1.05%
8%	1.038	1.095	5.2%	−1.30%

Notes: The welfare gains (compensating variations) of the Pigouvian and optimal toll in a city with an arbitrary *ad-valorem* tax rate (second and third column) are expressed relative to the respective gains in the city without property taxation. Therefore, a value above 1 does not signify a welfare level that exceeds that in the first-best, but merely a welfare gain from road pricing that exceeds the gain in absence of the housing tax. The percentage changes in relative welfare gains and city size refer to the transition from the Pigouvian to the *optimal tax interpolant* equilibrium.

to CBD, consequently decreasing the welfare gains from a Pigouvian toll (third row of Table 3) because commutes become shorter. Furthermore, the magnitude of the welfare effects in the two cases (*i.e.* first versus third row of Table 3) differs due to the initial spatial distribution of population, which is heavily skewed towards the CBD, and due to the way that distribution adjusts as a result of the Pigouvian toll.²⁴ Between the two polar cases, gradual expansion of the upper bound of the no-development area, z_U , produces non-monotonic results. In that case the direction of household relocation becomes ambiguous.

4.3. Optimal toll in the presence of ad valorem property taxation

We now investigate the role of a pre-existing tax induced distortion, by considering an *ad-valorem* tax (value tax) on housing property, paid by the consumer. We consider a wide range (0–8%) in order to capture the various levels of property taxation observed across Europe and North America. Because unpriced congestion is present in the benchmark city, this tax (at low levels) may be welfare improving: it generally reduces dwelling size, resulting in a more compact city where fewer vehicle kilometers are produced, thus replicating one of the outcomes of optimal road pricing. At the same time, the equilibrium tax per square meter is higher closer to CBD; this generates a *push-out effect* which increases urban sprawl and would thus increase congestion. Therefore, the total impact of the *ad-valorem* tax on welfare, as well as on the size of the city, is ambiguous.²⁵

The imposition of this policy generates a clear *tax interaction*: a location-specific tax for the use of the road coexists with a location-specific tax on property. However, this interaction is weak compared to other interactions investigated in relevant literature: for instance, a labor tax and a road toll might be perfect substitutes (from the viewpoint of policymaker) in settings where labor supply is inelastic in the intensive margin (fixed duration of working day, such as in Parry and Bento, 2001 or Verhoef, 2005) and there is no substitute transport mode for car.

As shown in the second column of Table 4, the welfare gains from a Pigouvian toll are generally stable across different levels of the *ad-valorem* tax. The third (fourth) column displays the gains (percentage difference in welfare gains) from the optimized road pricing scheme, based on the numerical optimal tax interpolant discussed in Appendix B. This is the numerically established tax schedule that maximizes social welfare. Despite the (numerical) difficulty to differentiate between the Pigouvian and the optimal tax at low levels of property taxation, the fourth column shows that the former is not the optimal one even at moderate levels of an *ad-valorem* tax. Intuitively, at higher levels of the property tax, the difference between the optimal and Pigouvian tax increases, reflecting the increased marginal excess burden of that tax.

²⁴ The welfare effects of no-development areas *per se* are negative. That is, equilibria with a larger no-development area, $x_U - x_L$, are associated with lower utility, despite the fact that the Pigouvian toll might produce larger welfare gains.

²⁵ These effects relate to those reported by Brueckner and Kim (2003), who examine the connection between property tax and city size. They show that two opposite effects come into play when the property tax rate increases. First, the tax exerts a depressive effect on structural density, which tends to increase city size; second, a higher property tax rate increases the private cost of housing provision, resulting in smaller dwellings. Then, if the elasticity of substitution between housing and other sources of utility (*e.g.* generic consumption) is zero, *i.e.* if preferences are Leontief, the second effect is eliminated and the property tax has an unambiguous positive effect on city size.

Fig. 3. Optimal road tax in the presence of a distortionary property tax.

Notes: Left panel: property tax rates at 4%; middle panel: property tax at 6%; right panel: property tax at 8%; short-dashed curve: marginal external cost of congestion; solid curve: optimal tax interpolant; long-dashed curve: deviation.

As Fig. 3 shows, the optimal road tax lies below the Pigouvian level. This implies that the interaction between the road toll and the property tax is negative. That is, the Pigouvian toll erodes the base of the property value-tax by reducing apartment sizes, city size and thus total floor space stock of the city. Note that, despite the fact that interpolation yields a strictly monotonous, concave price scheme, the total toll is negative in a considerable space interval, in all three cases. In fact, forcing the tax to be non-negative in the entire interval $(0, \bar{z})$ exhausts almost all of the additional gains from the road tax.

This implies that, to a large extent, these gains stem from household relocation closer to CBD, revealing that the non-congestion benefits from a downward adjustment of the toll close to CBD (and therefore attracting households close to CBD) outweigh the losses from non-optimal pricing of the congestion externality. The optimal tax interpolant provides a general downward adjustment and local corrections which account for the inefficiency of the property tax. These adjustments, which may not be feasible without the use of an additional policy instrument, can provide considerable improvements in terms of welfare gains.

5. Concluding remarks

This paper has investigated road pricing policies in the presence of various types of rigid distortionary housing market regulations, which cannot be lifted or adjusted by the authority that sets the road tax. The topic is highly relevant because the existing quantity restrictions in land and housing markets, especially command-and-control regulations such as maximum building heights and urban growth boundaries, might be incomparably more difficult to adjust than tolls in a road pricing scheme. Given such quantity restrictions, the Pigouvian tax rule remains optimal. However, the Pigouvian toll ceases to be optimal when a tax-induced housing market distortion is present, and is inferior to the second-best optimal toll.

The numerical application of the study focused on the presence of maximum floor-to-area ratio and no-development areas. It was demonstrated that the welfare gain from a Pigouvian toll is a non-monotonic function of the building height regulation stringency. This non-monotonicity is the consequence of two major, but opposing, effects that a Pigouvian toll generates. First, welfare gains on the road increase as the maximum building height is reduced, because travel distances and congestion costs increase everywhere within the monocentric city. Second, the implementation of a Pigouvian road pricing rule causes losses in housing market, which are more severe at milder levels of the FAR restriction. With no-development areas, the second result is absent, as the introduction of a Pigouvian pricing scheme does not affect land use efficiency in the developed areas. The welfare effects of road pricing are then entirely determined on the road. Finally, it was demonstrated that a property tax may have a negative tax interaction with a road tax, consistent with both taxes inducing more compact development. However, the results suggest that the effect is much weaker than the respective interaction effect between a road tax and the labor income tax. As a result, the additional welfare gains of an optimal deviation from the Pigouvian tax rule are small.

Our findings bear significant policy implications. Our computations suggest that the Pigouvian toll imposed in a city with a mild, uniform over space, floor-to-area ratio restriction may produce up to 40% smaller welfare gains relative to the gains of a Pigouvian toll in a city without height restrictions. On the other hand, welfare gains might be 80% larger in a city with an extensive zoned area close to the CBD. Therefore, welfare gains of road pricing may not only differ widely across cities

with different housing market regulations but even between pairs of cities in which the development pattern is relatively similar.

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Appendix A. Notation: variables and parameters

Tables A1 and A2.

Table A1

Basic model variables.

z	distance from CBD	p	price of floor space
$\bar{z}$	city size	r	price of land
L	labor supply	R	exogenous price of capital
L^D	labor demand	K_Y^D	capital demand (firm)
$\hat{z}$	BHR boundary	y	composite good (numéraire)
$\hat{k}$	structural density	G	total government revenue
$\hat{s}$	floor-to-area (FAR) ratio	G_e	aggregate differential rents
M	disposable income	G_a	total opportunity cost of land
m	pecuniary commuting cost (per km)	G_P	property tax revenue
τ_z	total road tax from z to CBD	G_R	toll revenue
B	lump-sum income	n	population density at distance z
ℓ	leisure time	K	total capital costs
t	commuting time	N	exogenous population
s	apartment size	$\bar{h}$	policy imposed FAR ceiling

Table A2

Model parameters and their values in the benchmark calibration.

Parameter	Value	Parameter	Value
α	7.0	g	0.01
β	0.11	N	1.0
γ	0.9	T	1.0
δ	0.8	m	417.5
ρ	0.2	r_A	10.0
t_0	0.02	p_K	1.0
t_1	0.12	ζ	0.2

Appendix B. Computational details

Solution algorithm

The model discussed in Section 2 has been programmed in C#, using Microsoft Visual Studio. Below we illustrate the algorithm used to solve for the general equilibrium, as the latter was presented in Sections 2.1–2.6. All integrals presented in the paper are approximated with high granularity, i.e. with the use of 200 points (400 points for the equilibria with BHR), here denoted by the sequence $\{z_0, z_1, \dots, z_{199}\}$. For the sake of exposition, an arbitrary point is denoted by z_i ; points are selected such that $z_{i+1} - z_i = z_i - z_{i-1} = \delta$ if $i > 0$ and $i < 199$. To approximate any integral in the interval $(0, \bar{z})$ we use:

$$\int_0^{\bar{z}} f(x) dx = \sum_{i=0}^{I-1} \int_{z_i}^{z_{i+1}} f(x) dx \approx \sum_{i=0}^{I-1} \left(\delta \left(\frac{f(z_i) + f(z_{i+1})}{2} \right) \right) \quad (\text{B1})$$

where $z_i = (i / I) \bar{z}$

Consider first the module $A(\bar{z}, u, w, t_z, B)$:

```

input:  $\bar{z}, u, w, t_z, B$ 
for  $= 0$ , while  $i < I$ :
  update  $z_i = (i / I) \bar{z}$ 
  compute  $M(z_i)$ , using (6); compute  $v(z_i)$  using (5); update  $p(z_i, u)$  using (11); update (7), (8), (9); update (3); update (15); update (16); update (14);
update (18), update (19); update (20);
   $i = i + 1$ 
end
update (22);
output:  $t'_z$ 
Next, consider the following fixed point iteration,  $\mathcal{F}$ :
while ( $t'_z - t_z > \varepsilon_{FP}$ )
   $t_z = t'_z$ 
  execute  $A(\bar{z}, u, w, t_z, B)$ 
end

```

Finally, the equilibrium can be reached by solving the square system containing Eqs. (24)–(31) in endogenous variables p_y , G , Q , B , $\bar{z}$, u , w and Y . We employ the Newton method with a finite difference approximation of the Jacobian matrix. The closure condition in (32) and the normalized price of the numeraire are excluded from the system in order for it to be identifiable (Walras law). The computation of (32) is one of the validity checks that can be performed upon convergence to validate that the equilibrium has been reached. Any time one of the endogenous variables G , Q , B , $\bar{z}$, p_z , w or Y is perturbed (for instance to approximate the Jacobian matrix of the system) the fixed point iteration is called prior to updating Eqs. (24)–(31).

Tax interpolation and direction set optimization

We have divided the road intervals $(0, \hat{z})$ and $(\hat{z}, \bar{z})$ in two and (respectively) three segments of equal length. The points that define these segments are given by the vector:

$$\delta' = 0, 0.33 \hat{z}, 0.66 \hat{z}, \hat{z}, \hat{z} + 0.33 (\bar{z} - \hat{z}), \hat{z} + 0.66 (\bar{z} - \hat{z}), \bar{z} \quad (\text{B1a})$$

when FAR regulations are present and by the vector:

$$\delta' = 0, 0.250 \bar{z}, 0.50 \bar{z}, 0.75 \bar{z}, \bar{z} \quad (\text{B2})$$

when not. Define any pricing scheme in the paper as a vector $\mathbf{c}'$ of equal size as δ' , and let $\mathbf{c}'_i$ denote the total price charged to the household located at distance δ'_i . Under piecewise linear interpolation, for any $\delta'_i < z < \delta'_{i+1}$, the charge is given by:

$$c_z = \mathbf{c}'_i + \frac{z - \delta'_i}{\delta'_{i+1} - \delta'_i} (\mathbf{c}'_{i+1} - \mathbf{c}'_i). \quad (\text{B3})$$

Under (non-linear) Lagrange interpolation, we define the Vandermonde matrix:

$$\mathbf{V} = \begin{bmatrix} 1 & \delta'_0 & \delta'^2_0 & \delta'^3_0 & \delta'^4_0 \\ 1 & \delta'_1 & \delta'^2_1 & \delta'^3_1 & \delta'^4_1 \\ 1 & \delta'_2 & \delta'^2_2 & \delta'^3_2 & \delta'^4_2 \\ 1 & \delta'_3 & \delta'^2_3 & \delta'^3_3 & \delta'^4_3 \\ 1 & \delta'_4 & \delta'^2_4 & \delta'^3_4 & \delta'^4_4 \end{bmatrix} \quad (\text{B4})$$

and solve $\mathbf{V}\mathbf{a} = \mathbf{c}$ for the coefficient vector $\mathbf{a}$ which is used to construct the interpolating polynomial:

$$c_z = \mathbf{a}'_0 z^0 + \mathbf{a}'_1 z^1 + \mathbf{a}'_2 z^2 + \mathbf{a}'_3 z^3 + \mathbf{a}'_4 z^4. \quad (\text{B5})$$

Throughout the paper, the expressions in (B3) and (B5) are called *tax interpolants*. Any optimization technique employed attempts to approximate the vector $\mathbf{c}'$ that belongs to policy space and maximizes ((10) subject to the equilibrium conditions.

Appendix C. Numerical illustration of Pigouvian optimality

To illustrate the optimality of the Pigouvian toll, we perform a series of numerical computations based on the idea that the toll function in (23) can be approximated with the use of a piecewise linear interpolant (see Appendix B). Then, the optimal tax at the selected points used in the interpolation (distances from CBD) can be computed with standard numerical optimization techniques. We use starting values that account for 70% of the Pigouvian toll in the interpolation points. Various different levels of initial perturbations have been tried and resulted in slightly different relative efficiencies; however, the general result remains intact: in none of the cases has the relative efficiency been observed to fall below 1.0. Table C displays the efficiency of the Pigouvian toll relative to the optimized tax interpolant.

To establish that the result does not depend on the assumed elasticity of substitution, the computations are repeated for two different cities in which σ is lower (higher). In each case, the model parameters are recalibrated in order for the base

Table C

Relative efficiency of the Pigouvian toll (benchmark: optimal tax interpolant).

Elasticity of substitution (σ)	0.40	1.25	1.54
Maximum FAR allowed			
15.0	1.014	1.035	1.025
10.0	1.009	1.011	1.010
6.00	1.006	1.008	1.002

Notes: All results in the table produced with linear piecewise interpolation and Newton–Raphson with line search.

equilibrium to loosely resemble the unregulated equilibrium of Section 4.1. The results are displayed in the second (fourth) column of Table C.

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