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Evaluating on-street parking policy

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EVALUATING ON-STREET PARKING POLICY

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Abstract*

This paper uses a formal model to examine the welfare gains from a marginal increase in the price of on-street parking. The benefits of such a policy are shown to depend on the improvement in search externalities in the on-street parking market itself, plus effects on other distorted urban transport markets, including congested freeway and backroad use, mass-transit and off-street parking.

The paper makes two further contributions. The model is sufficiently general that several well-known results from the parking literature emerge as special cases. The model is used to review the existing literature and highlights findings in separate parts of literature. Finally, a numerical simulation model is used to investigate the order of magnitude of an optimal urban parking fee. In particular, these results confirm the importance of taking into accounts effects on other distorted transport markets when deciding upon the level of the price for on-street parking. The model confirms that while parking pricing reform may lead to substantial improvements in parking search times, there is little overall impact on road congestion levels.

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Evaluating on-street parking policy

I. Introduction

The economics of parking has traditionally been something of an ‘ugly sister’ in the field of transport economics research. Only a handful of articles appear in the mainstream literature[1]. And this is despite the fact that nearly all cities intervene on a regular basis in the urban parking market. The majority of the literature is devoted instead to sophisticated pricing solutions to the problems of congestion and air pollution, such as road tolls, which almost no cities have adopted.

This paper uses a formal model to identify the welfare impact of policy intervention in the on-street parking market. The current literature stresses two policy objectives, usually separately. Firstly, an unregulated parking market results in too many drivers spending too long searching for a limit supply of spaces, at least in the peak-period. Secondly, parking fees can be used as a second-best alternative to road congestion tolls. Our findings confirms this intuition but stresses a broader range of criteria. Policy assessment requires knowledge of the impacts on search times in the on-street parking market, plus a range of effects on distorted *secondary* transport markets. One of these effects includes, of course, the impact on congested road use. However, in addition, we stress the potential effects on the off-street parking market and the mass transit market.

Section II presents the model and derives the central expression for the welfare impact of a revenue-neutral increase in on-street parking fee. This result collapses as a special case into several well-known results in the literature. Section III therefore uses the model result to review the existing literature. In doing so, the connection between results from the road congestion and the parking literature is stressed.

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[1] Piet Rietveld remarked that while the average car is parked for over 95 per cent of the time, and thus actually being driven for less than 5 per cent of the time, a review of the transport literature might very well lead you to conclude that the figures are the other way around.

Whilst the theoretical model highlights the potential importance of distortions on secondary transport markets in determining efficient parking policy, practical price setting requires estimation of the likely magnitude of such impacts. Section IV provides a numerical model which illustrates the importance of the relative elements of the theoretical model. Section V concludes and provides suggestions for future research.

II. Model

A representative consumer derives utility from consumption of leisure, ℓ, a composite commodity, C and a vector of travel services[2], T. Travel services consist of trips across two modes (auto and rail), and, when travelling by car, two route choices (freeway F and backroad B) and two parking markets (on-street X and off-street Y). All trips are assumed to take place in the peak-period[3]. Rather than examine all possible combinations, we consider a set J containing 5 markets, as shown in Table 1.

Table 1 - transport markets

j	transport market
FX	Freeway, parking on-street
FY	Freeway, parking off-street
BX	Backroad, parking on-street
BY	Backroad, parking off-street
R	Rail

Hence, consumer utility is defined by

[2] This model follows an approach set out in Parry and Bento (2002).
[3] In Calthrop (2001), the model also allows for choice of time period: peak versus off-peak. Inclusion of the off-peak is only relevant if distortions are present in the off-peak.

$$U = u(C, \ell, T_j) \qquad (1)$$

where T_j gives the number of trips per time period of type j, where $j \in \{FX, FY, BX, BY, R\}$. We assume a fixed transport infrastructure. Figure 1 shows the corresponding network graph.

INSERT FIGURE 1 AROUND HERE

The time required to complete a single trip[4] is denoted by ϕ_j. Road use is assumed to be congestion-prone and hence travel time depends on the number of trips using the same infrastructure. Thus, we denote the time required to drive along the freeway and backroad by $\phi_F(T_{FX} + T_{FY})$ and $\phi_B(T_{BX} + T_{BY})$ respectively, with $\phi_F' > 0, \quad \phi_B' > 0$.

Similarly, on-street parking is assumed to require search time, which depends on the number of other drivers parking on-street. Thus, we denote this search time by $\sigma(T_{FX} + T_{BX})$, with $\sigma' > 0$. Parking off-street, in contrast, is assumed to be congestion free, and thus the time required to park is constant (and, for ease, set equal to zero).

Thus, for road trips, we summarise:

$$\begin{array}{ll} \phi_{FY} = \phi_F & \phi_{BY} = \phi_B \\ \phi_{FX} = \phi_F + \sigma & \phi_{BX} = \phi_B + \sigma \end{array} \qquad (2)$$

A rail trip is assumed to require a constant length of time[5], ϕ_R. The consumer time constraint is given by:

$$L + \ell + \sum_j \phi_j T_j = \overline{L} \qquad (3)$$

where $\overline{L}$ is the total time endowment.

[4] We assume a static congestion function: Section III.3 provides further information on dynamic modelling and some comparison with results presented here.
[5] It is straightforward to allow for rail congestion – however, to simplify matters, we abstract from this here. In addition, we abstract from waiting time and service frequency issues.

The consumer money price of a trip is denoted by θ_j. Government is assumed to be able to set a road toll on freeway trips, τ, but not on backroads. In addition, government can set the price of on-street parking, p_X, off-street parking, p_Y and the fare for rail, f. The producer price of a road trip, produced under constant returns to scale, is given by $\tilde{\theta}_r$ where $r \in \{F, B\}$. We summarise consumer prices by:

$$\begin{aligned} &\theta_{FX} = \tau + p_X + \tilde{\theta}_F && \theta_{FY} = \tau + p_Y + \tilde{\theta}_F \\ &\theta_{BX} = p_X + \tilde{\theta}_B && \theta_{BY} = p_Y + \tilde{\theta}_B \\ &\theta_R = f && \end{aligned} \tag{4}$$

The consumer budget constraint is given by:

$$C + \sum_j \theta_j T_j = L + G \tag{5}$$

where G denotes a lump-sum transfer and units are adjusted such that the price of labour supply and the composite good are equal to 1.

Production is under constant returns to scale, except for the rail sector, which produces under increasing economies of scale, with a fixed cost element, F and a constant marginal cost, $\tilde{\theta}_R$. The fixed supply of on-street parking is provided at zero opportunity cost[6], whilst off-street parking is provided at constant marginal cost, m_Y. The material balance condition for this economy is thus:

$$L = C + \sum_{j=FY,BY} (\tilde{\theta}_j + m_Y) T_j + \sum_{j=FX,BX,R} \tilde{\theta}_j T_j + F \tag{6}$$

The government budget constraint requires that:

$$\begin{aligned} &G + F + \tilde{\theta}_R T_R + m_Y (T_{FY} + T_{BY}) = \\ &\quad \tau(T_{FX} + T_{FY}) + p_X (T_{FX} + T_{BX}) + p_Y (T_{FY} + T_{BY}) + f T_R \end{aligned} \tag{7}$$

[6] This assumption simplifies matters. It is consistent with the assumption of a fixed supply of on-street spots. In the longer term, the opportunity cost of spots is positive. It is often argued, for instance, that on-street spots could be used to widen the existing urban street and thus reduce congestion. However, traffic engineers compute road capacity in terms of junction capacity. Removing parking spots is likely to have no impact on junction capacity, and thus opportunity cost may be very low.

The representative consumer maximises utility, expression (1), with respect the quantities of the composite good, leisure and transport, subject to a budget constraint, (5) and a time constraint, (3), taking the level of prices, the lump-sum transfer, time required to drive a kilometre and to search for a parking spot as parametric. Substituting the resulting demand functions into the utility function gives an indirect utility function: $V(p_X, p_Y, \tau, f, G, \phi_F, \phi_B, \sigma)$. We assess the welfare impact of a marginally increasing the on-street parking fee, whilst returning revenues via the lump-sum transfer in order to balance the government budget constraint. Ignoring constant terms therefore gives an indirect utility function defined by:

$$V(p_X, G, \phi_F, \phi_B, \sigma) \tag{8}$$

As derived in Annex 1, the welfare impact of a revenue-neutral increase in the on-street parking fee can be written as the sum of five terms:

$$\frac{1}{\lambda}\frac{dV}{dp_X} = dW_X + dW_Y + dW_F + dW_B + dW_R \tag{9}$$

where[7]:

$$\begin{aligned}
dW_X &= (MEC_X - p_X)(-\left\{\frac{dT_{FX}}{dp_X} + \frac{dT_{BX}}{dp_X}\right\}) \\
dW_Y &= (p_Y - m_Y)\left\{\frac{dT_{FY}}{dp_X} + \frac{dT_{BY}}{dp_X}\right\} \\
dW_F &= (MEC_F - \tau)(-\left\{\frac{dT_{FX}}{dp_X} + \frac{dT_{FY}}{dp_X}\right\}) \\
dW_B &= MEC_B(-\left\{\frac{dT_{BX}}{dp_X} + \frac{dT_{BY}}{dp_X}\right\}) \\
dW_R &= (f - \tilde{\theta}_R)\frac{dT_R}{dp_X}
\end{aligned} \tag{10}$$

and

[7] The change in demand is presented as a total derivative. As shown in Calthrop, De Borger and Proost (2002), this total derivative can be decomposed to account explicitly for reactions in demand from increasing the price of parking, from feedback effects via changes in congestion levels and from altering the level of the lump-sum transfer. In order to stress the intuition of the model results, we prefer to present in total derivative terms.

$$MEC_X = \frac{\mu}{\lambda}\sigma'\left(T_{FX} + T_{BX}\right) \qquad MEC_F = \frac{\mu}{\lambda}\phi_F'\left(T_{FX} + T_{FY}\right)$$

$$MEC_B = \frac{\mu}{\lambda}\phi_B'\left(T_{BX} + T_{BY}\right)$$

Each component can be examined in turn. The first term, dW_X, gives the welfare effect on the on-street parking market. It equals the general equilibrium reduction in demand multiplied by the 'distortive wedge' on the on-street parking market. The wedge is equal to the gap between marginal external search cost, MEC_X and marginal benefit, given by the price. The marginal external search cost equals the utility loss (measured in income terms) to other on-street parkers from increasing the average time required to search for an on-street parking spot. If the analysis is restricted to the on-street parking market alone, welfare is improved by marginally increasing the on-street price from any level below the marginal external search cost. If the price is equal to marginal external search cost, which I refer to henceforth as the Pigouvian price: $p_X^{PIG} = MEC_X$, there are no further welfare gains to be had from the on-street market, $dW_X = 0$.

The theory of the second best shows that welfare analysis of policy measures aimed at correcting one market imperfection (in this case reducing search externalities) needs to account for induced effects on other distorted markets. The remaining four terms in equation (9)relate to pre-existing distortions on *secondary* markets i.e. markets other than the on-street parking. Simple Harberger theory teaches that the welfare assessment on secondary markets takes the form of a distortionary wedge, in this case the difference between price and marginal social cost, multiplied by the resulting (general equilibrium) change in demand. The remaining four terms in equation (9) take this form.

The second term, dW_Y, takes account of pre-existing distortions on the off-street market. Assume that off-street market is taxed, i.e. $p_Y > m_Y$. Hence the marginal benefit of off-street parking exceeds marginal cost. If on- and off-street parking are substitutes (in total derivative terms), increasing the on-street fee alleviates the pre-existing distortion on the off-street market. Conversely, if the off-street market is subsidised, the distortion is exacerbated.

The third term, dW_F, accounts for distortions arising from congestion on the freeway. If congestion is underpriced, ($\tau < MEC_F$) or not priced at all, the marginal social cost of freeway use is greater than the marginal benefit. Thus, as long as higher on-street parking fees reduce freeway use, the presence of underpriced congestion increases the benefit from raising parking fees. The fourth term, dW_B, is entirely analogous to the third term, though relating to backstreet congestion. Recall that, by assumption, no charge can be placed on backroad use and hence the marginal social cost exceeds the marginal benefit.

The final term, dW_R refers to the rail market. Again, to the extent that rail travel is distorted (in practice, usually via an operating subsidy such that $f < \tilde{\theta}_R$), the welfare gain from reforming parking prices will need to account for induced effects on the distorted rail market.

III. Reviewing the on-street parking literature

The literature broadly falls into two camps. One group of authors focuses on search externalities, and derives the optimal price for on-street parking while abstracting from issues of underpriced road congestion or other market distortions. A second group abstracts from search externalities in order to examine the optimal price of parking if road use is underpriced. Both these types of results can be presented as a special case of equation (9). Hence in this section we use the conceptual framework provided by our model to review the existing parking literature. However, it is worthwhile stressing that parking policy should account for all elements of equation (9), and not just the special cases considered below. This point is reinforced by the results of a numerical simulation model in Section IV below.

III.1. On-street Pigouvian fee

Assume that secondary markets are not distorted i.e. $dW_Y = dW_F = dW_B = dW_R = 0$. Setting equation (9) equal to zero gives that the optimal parking fee is equal to the Pigouvian level: $p_X^* = p_X^{PIG} = MEC_X$. This idea appears, albeit in a slightly varied forms, in a number of papers in the literature.

Arnott and Rowse (1999) demonstrate that the optimal price per time unit parked is equal to marginal external search cost: this is the additional search cost imposed on other would be parkers from the decision to stay for an additional unit of time. This simple welfare message emerges from a complex spatial model: drivers choose whether to make a trip, which mode of transport to employ, and, if travelling by car, when to start searching for a vacant parking spot. The symmetry of the spatial setting implies that the marginal external search cost (and hence the optimal fee) is independent of space. The stochasticity of the search process, however, results in multiple equilibria. For instance, adopting the terminology of the road congestion literature, there may exist a *hyper-congested* equilibrium, with relatively high average search costs, or *congested* equilibrium, with much lower average search costs. Policy intervention cannot guarantee decentralising any one equilibrium.

Anderson and de Palma (2002) consider a spatial model in which parking spots are imperfect substitutes for one another. An efficient spatial allocation of parkers is decentralised via a parking fee profile. At the optimum, the fee at each point in space is set equal to marginal external search cost – in this case the increase in search cost to other would be parkers in the immediate vicinity of the parking area. As spots closer to the centre are more desirable than those further away, the optimal parking gradient is falling in distance from the CBD. A simplified version of this result appears also in Verhoef *et al.*(1995a).

Calthrop and Proost (2002) abstract from spatial considerations to focus on the pricing of on-street space in the presence of a privately-operated off-street parking. If the on-street market is cheaper than the off-street market, drivers are induced to over-invest in socially wasteful searching. If the off-street market is competitive, the optimal on-street price is shown to equal the resource cost of off-street supply. However, if market power is exercised on the off-street market, the optimal pricing rule deviates, as can be predicted from equation (9) if $dW_Y \neq 0$.

The first discussion of optimal on-street pricing appears in a non-formal paper by William Vickrey (1959). He advocates peak-load pricing: given a fixed short run supply of urban parking space, the price of parking should be set such that demand equals supply. This is closely related to the idea of marginal external cost pricing. Vickrey goes on to consider peak-load pricing with uncertain demand. He advocates 'responsive-pricing', in which the price varies according to the number of vacant spaces in the nearby area. Thus, as demand rises, and the number of vacant spaces falls, the price of parking rises. However, as pointed out by Arnott and Rowse, this is only efficient if drivers know the full time profile of demand.

III.2. Second-best parking fee

As is well known, the efficiency of applying a second-best instrument relies on the degree of linkage between the instrument used and the externality affected. Verhoef *et al.* (1995a) discuss the degree of linkage between a parking fee and the decisions which affect congestion, namely departure time, route choice, mode choice and driving style. Several authors have formalised this argument, though these results can be considered as special cases of equation (9).

Case A: Two roads and one parking market

Consider a simplified version of our model. Assume that all parking occurs on-street (i.e. $T_{FY}, T_{BY} = 0$), abstract from search-cost externalities[8] ($MEC_X = 0$) and the rail market ($T_R = 0$). Figure 2 shows the network graph in this setting.

INSERT FIGURE 2 AROUND HERE

Drivers choose between the freeway and the backroad, with differing marginal congestion costs. The first-best solution requires a separate toll on each route. In the absence of road tolls, however, the parking fee may be used as a second-best instrument. Setting equation (9) to zero, substituting from (10), assuming $\tau = 0$ and manipulating, gives an implicit equation for the second-best parking fee:

$$p_X^* = \zeta MEC_F + (1-\zeta) MEC_B \qquad (11)$$

in which ζ gives the share of total demand reaction that occurs on the freeway:

$$\zeta = \frac{1}{\left(1 + \dfrac{\varepsilon_{BX} T_B}{\varepsilon_{FX} T_F}\right)}$$

and ε_{iX} gives the (total) own-price elasticity of market i with respect to a change in the price of on-street parking (market X).

The optimal second-best parking fee is a weighted average of the marginal external cost on the freeway and backroad. The weight given to the freeway external falls to the extent that freeway travel is relatively inelastic $\left(\varepsilon_{BX} / \varepsilon_{FX}\right) > 1$ or that freeway demand is relatively small $\left(T_B / T_F\right) > 1$. This is an intuitive and well-known result. The more elastic the demand

[8] In the absence of search cost externalities, we could also consider a specific tax on both on-and off-street parking. Indeed, as long as the off-street market is competitive, the results are identical to those derived here. To make the link with the literature, however, we prefer the simplified setting.

curve, the greater the distortion if price deviates from marginal external cost. The optimal parking fee therefore places greater weight on the market with the higher elasticity of demand. Verhoef *et al.* (1995b) derive a similar result.

Case B: One road and two parking markets

If the government controls only the price of on-street parking, higher prices may have little impact on congestion levels. Increasing the on-street price may induce most drivers to switch to parking off-street, but have little impact on overall congested road demand. This is similar to a point made by Glazer and Niskanen (1992) about through-traffic. Raising city centre parking prices may reduce the number of city-centre bound trips, but, by reducing congestion levels, may simply increase the amount of through-traffic.

This result emerges from a suitably simplified version of equation (9). Assume a single route ($F = B$), assume away search-costs ($MEC_X = 0$) and abstract from the rail market ($T_R = 0$). The network graph is shown in Figure 3.

INSERT FIGURE 3 AROUND HERE

Substituting the equation (10) into (9), setting $\tau = 0$ and solving for the optimal on-street parking price gives:

$$p_X^* = MEC\left(1 - \frac{\varepsilon_{YX} T_Y}{|\varepsilon_{XX}| T_X}\right) \tag{12}$$

where MEC denotes the marginal external congestion cost from using the single road. The optimal price is equal to the marginal external congestion cost multiplied by a factor, the magnitude of which depends on cross and own price effects. If a higher on-street price has no general equilibrium impact on the demand for off-street parking, $\varepsilon_{YX} = 0$, the optimal price is equal to marginal external cost. However, in general, we would expect a positive cross-price elasticity. The greater the cross-price effect (for any given own price elasticity), the less impact raising the on-street price has on congestion levels. Hence the smaller the optimal price. In the case that any reduction in on-street parking is entirely offset by off-street parking, the optimal parking fee is zero.

Equation (12) mirrors equation 18 of Glazer and Niskanen. In the terms of their model, if the reduction in city centre bound traffic resulting from the higher parking fee is entirely offset by increased through-traffic trips, the optimal fee falls to zero. A similar result also appears in Verhoef *et al.* (1995b).

Case C: Two roads and two parking markets

While the literature has considered two particularly simple examples of network structure, we can use equation (9) to consider a slightly more complex formulation. As stressed in Case B, government policy is often limited to pricing reform on the on-street market. Drivers can escape higher prices via the off-street market. In addition, as shown in Case A, the government is trying to charge for marginal external congestion costs across several different routes.

Consider our benchmark model , with two routes: freeway and backroad, and two parking markets: on-street and off-street. Abstract from on-street search externalities ($MEC_X = 0$), and assume marginal cost pricing on the rail market. Substituting the equation (10) into (9), setting $\tau = 0$ and solving for the optimal on-street parking price gives:

$$p_X^* = \zeta_F MEC_F + \zeta_B MEC_B \tag{13}$$

where:

$$\zeta_i = \frac{\left|\varepsilon_{iX,X}\right| T_{iX} - \varepsilon_{iY,X} T_{iY}}{\left|\varepsilon_{FX,X}\right| T_{FX} + \left|\varepsilon_{BX,X}\right| T_{BX}}$$

Expression (13) is, of course, a generalised version of equations (12) and (11)[9]. Higher relative weight is placed on the marginal external cost from the link with the largest absolute value of own-price elasticity and with the lowest cross-price elasticity. The overall level of the tax falls with the absolute value of the own-price elasticity.

Consider an extreme assumption. All freeway trips park on-street and all backroad trips park off-street[10]. Hence $T_{FY} = T_{BX} = 0$. Such a network is shown in Figure 4.

INSERT FIGURE 4 AROUND HERE

In this case, equation (13) reduces to a well-known expression:

$$p_X^* = MEC_F - MEC_B \left[\frac{\varepsilon_{BY,X} T_{BY}}{\left|\varepsilon_{FX,X}\right| T_{FX}} \right] \qquad (14)$$

This is just the second-best pricing rule for a single land in the presence of an untolled alternative, as first derived by Lévy-Lambert (1968) and Marchand (1968).

Second-best pricing rules can be analytically or numerically derived in more complex network structures (see Verhoef, 2002 and Van Dender, 2001). Assuming away search costs, the intuition for the pricing rule emerging from more complex models remains equation (13). However, as stressed in the conclusions below, a central research question remains as to how the search process can be modelled on realistic networks.

III.3. Dynamic models

Our model is static in nature. This section reviews the on-street parking literature that adopts an explicitly dynamic setting. Arnott, de Palma and Lindsey (1993) present the basic

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[9] If $\varepsilon_{iY,X} = 0$, i.e. there are no cross-price effects, expression (13) reduces to (11). Similarly, if all terms relating to the backroad are eliminated, expression (13) reduces to (12).

bottleneck model of road congestion. Drivers choose the time of departure by trading-off schedule delay costs, from arriving too early or too late at the desired destination, against expected queueing costs. In equilibrium, the total cost of a trip is the same for all drivers regardless of departure time. The optimal congestion fee is time-differentiated, such that drivers are induced to arrive at the bottleneck at exactly the maximum through-put rate. However the authors also consider a time independent fee, which can be straightforwardly interpreted as a parking fee. In our static setting, note, with a single route and a single parking market, the parking fee can be set equal to marginal external congestion cost. Since this cost is static, this is a first-best result. In the dynamic setting of Arnott *et al*., however, a uniform parking fee does not alter the incentives for driver departure time. The optimal parking fee is therefore second-best in nature: it is set equal to marginal external cost, given inefficient departure times.

In a follow-up paper, Arnott *et al* (1991) examine the optimal spatial profile of parking fee. In the absence of a parking fee, drivers arriving relatively early for work park closest to the workplace, while late arriving drivers park further away and have to walk i.e. parking occurs ‘outwards’. The authors show that aggregate travel costs are minimised by inducing drivers to park inwards. Total walk costs remain unchanged by the order of parking, while schedule delay costs are reduced by having early drivers arrive slightly later and later drivers arriving slightly earlier. The optimal spatially differentiated parking fee (in the presence of an optimal time varying congestion fee) falls with distance from the city centre. The authors also solve for the optimal second-best parking fee profile in the absence of a congestion toll.

Calthrop *et al*., (2000) compute the optimal time-independent parking fee in a numerical simulation model of Brussels. The model contains a single link and captures dynamic aspects in a reduced-form manner, with an exogenously specified peak and off-peak

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[10] This may not be so unrealistic. If traffic arriving from the north of the city parks in a separate area to traffic arriving from the south, and, perhaps due to a one-way system, crossing from one parking area to another is difficult, our assumptions are approximately met.

period. The optimal parking fee is a weighted average of the external congestion costs in the peak and off-peak periods. As such, it is similar in spirit to equation (11) above. However, the model contains numerous externalities (congestion, local air pollution, global warming effects, noise and accidents) and captures impacts on a distorted labour market via a marginal cost of public funds parameter. The optimal second-best parking fee is computed at approximately three times the marginal resource cost of an urban parking spot.

IV. Numerical Model

Typically, the literature has stressed either the need to set prices to internalise search externalities or the need to second-best price road congestion[11]. However, we have seen in equation (9), any welfare assessment of an increase in on-street prices needs to account for effects on a whole vector of transport markets: the on-street parking market, the off-street parking market, the market for congested road use and the market for mass transit[12]. We employ an applied general equilibrium model[13] to gauge an impression of the likely order of magnitude of optimal on-street prices. The results are not intended to be city-specific. Rather the model is calibrated to a 'typical' urban area, using similar parameter values to Parry and Bento (2002).

IV.1. Model Structure

Each consumer maximises utility function which is given by:

$$U = CES(C, \ell, T) \tag{15}$$

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[11] One exception is Anderson and de Palma (2002) who integrate both concerns in one model.
[12] Strictly speaking, of course, this principle extends to distorted non-transport markets, including possibly labour and housing market.
[13] The model is constructed using MPSGE in GAMS. The original version of this model was developed by Tom Rutherford and can be consulted at http://robles.colorado.edu/~tomruth/congest. The model code employed by Parry and Bento (2002) can also be found at http://www.rff.org/~parry/links/transp3.htm.

with an elasticity of substitution parameter denoted by σ_U, where aggregate travel services, T is an aggregate of rail transport, freeway and backroad use and composite off-peak travel[14] and is given by:

$$T(T_R, T_{FB}, T_{OP}) = \left\{ T_R^{\frac{\sigma_R - 1}{\sigma_R}} + \left(\left[T_{FB}^{\frac{\sigma_T - 1}{\sigma_T}} + T_{OP}^{\frac{\sigma_T - 1}{\sigma_T}} \right]^{\frac{\sigma_T}{\sigma_T - 1}} \right)^{\frac{\sigma_R - 1}{\sigma_R}} \right\}^{\frac{\sigma_R}{\sigma_R - 1}}$$

and aggregate peak-period auto trips, T_{FB} is given by

$$T_{FB} = CES(T_F, T_B)$$

with parameter σ_L, and, in turn, aggregate freeway trips is given by:

$$T_F = CES(T_{FX}, T_{FY})$$

with parameter σ_P. The corresponding measure for aggregate backroad trips is also CES in T_{BX} and T_{BY} with the same substitution parameter as for the freeway market, σ_P. The representative consumer maximises utility (15) subject to a budget constraint (5) and a time constraint (3).

IV.2. Calibration

A. Travel time

The following functional form for the road congestion function is assumed:

$$\phi_j = \overline{\phi}_j \left\{ 1 + \gamma \left[\frac{T_{jX} + T_{jY}}{CAP_j} \right]^k \right\} \tag{16}$$

[14] This market is an addition from the analytical model. However, we assume no distortions on this market. Its central purpose is to aid calibration of the model to existing data.

where $j \in \{F, B\}$, CAP_j is a measure of road capacity and $\overline{\phi}_j$ is the time required for a journey under freeflow (i.e. non-congested) conditions. This specification is the well-known 'Bureau of Public Roads' formula – see Small (1992). Following the literature, we assume values of $\gamma = 0.15$ and $k = 4$. Initial freeway demand and capacity are chosen such that the peak-period speed is one half of free-flow speed in the benchmark equilibrium. For backroads, an equivalent figure of two-thirds is chosen.

There is little evidence on the functional form of parking search time. Axhausen (1994) relates average search time to the ratio of demand to supply. This is taken as justification to employ the functional form in (16) for search time. Capacity is chosen such that finding a vacant spot takes twice the time in free-flow conditions.

B. Transport shares and benchmark prices

Following Parry and Bento (2002), we assume the following benchmark shares of generalised transport expenditures: peak-freeway 0.33; peak-rail 0.33; peak-backroads 0.17 and off-peak 0.17. It is assumed that freeway and backroad demand is split equally between on-street and off-street parking.

Benchmark money and time expenditures are given in Table 2. The first row gives the money price (excluding parking costs) for each mode. The price of freeway is normalised to one. This can be compared with a total generalised price of 2.2. The money prices of freeway and backroad use are set equal as trip distance is assumed to be equal and differences in operating costs, given different driving speeds, is ignored. In the benchmark case, no toll is charged on freeway or backroad use. Furthermore, it is assumed that rail use is subsidised at 50 per cent of the operating cost – this figure obviously varies greatly between cities and countries, but our figure lies within the range of estimates (see De Borger and Proost (2001) for a review in European countries).

Table 2 Benchmark shares of generalised expenditures

expenditures	FX	FY	BX	BY	R	OP
money (excl. park)	1	1	1	1	0.25	1
uncongested road time	0.5	0.5	0.66	0.66	1.5	0.5
congested road time	0.5	0.5	0.34	0.34	0	0
uncongested search time	0.1	0	0.1	0	0	0
congested search time	0.1	0	0.1	0	0	0
money park	0	0.5	0	0.5	0	0
total generalised price	2.2	2.5	2.2	2.5	1.75	1.5

The second and third rows give the time expenditure required per trip. For auto trips, a distinction is made between the time required under non congested conditions (second row) and as a result of congestion (row 3). As discussed in the previous section, the congestion function is such that a freeway trip takes twice the length of time required under uncongested conditions, while a backroad trip takes one and a half times the time under uncongested conditions. Rail and off-peak travel are assumed uncongested.

The fourth and fifth rows give corresponding figures for park search time expenditures. The share of total journey time devoted to searching for a parking spot is based on a review in Axhausen (1994) for European and North American cities. The sixth row gives the price of parking. It is assumed that the off-street market is competitive and thus the money price is equal to the resource cost. On-street parking, in the benchmark scenario, is assumed to be free.

C. Elasticities of substitution

The magnitude of responses to policy are to a large extent driven by the choice of elasticities of substitution in demand. Table 3 presents the model assumptions.

Table 3 Elasticities of substitution

EOS	value
σ_U	0.6
σ_R	0.8
σ_T	1.0
σ_L	1.4
σ_P	2.5

These parameter values imply an own-price elasticity of freeway demand of –0.3, and cross price elasticities of 0.12 (backroad); 0.06(off-peak) and 0.03 (rail). These appear to be within the range of empirical estimates – see the Annex of Calthrop *et al.* (2000) for a review. The own-price elasticity for on-street parking is –0.37, while cross-price elasticities are equal to 0.16 (off-street); 0.04 (off-peak) and 0.02 (rail). The (partial) uncompensated elasticity of labour supply is 0.21. This seems to be in line with the general literature (see Fuchs *et al.(*1998), and is close to the figure used by Parry and Bento (2002).

IV.3. Model Results

The welfare gain from a revenue-neutral marginal increase in the price of on-street parking is shown in Figure 5. The horizontal axis shows the tax rate as a percentage of the reference money price per auto-trip (recall that this is assumed independent of route choice). The vertical axis gives the welfare gain from the marginal tax increase.

INSERT FIGURE 5 AROUND HERE

Three lines are shown on the Figure: the line marked 'Benchmark' gives a linear finite approximation to the marginal welfare gain from raising the tax rate under the assumptions of the benchmark scenario. Recall that these are characterised by:

- no congestion toll ($\tau = 0$);
- marginal cost pricing on the off-street parking market ($p_Y = m_Y$); and,
- a 50 per cent rail operating subsidy ($f = 0.5m_R$).

Welfare gains are positive from raising the on-street parking fee until approximately equal to 19 per cent[15] of the reference money price of a trip.

Two other lines are marked. The line marked 'Pigouvian' shows the marginal welfare gains if optimal congestion tolls are in place and rail is priced at marginal cost. The optimal tax rate is approximately equal to 0.09, or less than one-half of the benchmark level. Were policy-makers to fail to account for the impacts on other distorted markets (in this case, the congested auto markets and subsidised rail market), on-street prices would be set at a sub-optimally low level.

In order to separate out the effects of the separate distortions on the rail and congested road markets, the third line presents model results assuming that rail is priced at marginal cost – and hence is marked as MC RAIL. The optimal parking fee is set slightly higher than in the benchmark scenario. As shown in equation (9), if the rail market is subsidised, raising the price of parking exacerbates the rail distortion. Hence, in the benchmark scenario, optimal parking prices are set lower than in MC RAIL.

[15] Some readers may prefer results in absolute money values. For Brussels, De Borger and Proost (2001) estimate the money price of an average trip to equal approximately 1.5 € (average trip distance

Recall also that the marginal external congestion costs differ between the backroad and the freeway. The optimal second best parking price reflects a weighted average of the two, where elements of the weights were given in equation (13).

Further model output is given in Calthrop (2001). Summarising, however, the welfare gains even under optimal pricing remain limited: most of the reduction in on-street parking demand switches to the off-street market. Hence the improvement in congestion levels is small. Freeway trip time reduces only by 1.5 per cent. This confirms a general view in the literature that the reform of parking pricing is unlikely to produce large reductions in congestion levels. However, the reduction in parking search time is more substantial: the density of vacant spaces increases by approximately one-third.

One sensitivity test[16] is worth stressing. The benchmark model assumes that the off-street market is competitive. Figure 6 repeats the benchmark model results, but also shows two further model runs: one in which the off-street parking market is subsidised at 50 per cent and with a tax of 50 per cent. This latter scenario can be loosely thought of as a mark-up from non-competitive supply.

INSERT FIGURE 6 AROUND HERE

In accordance with the intuition from equation (9), optimal on-street fees are considerably smaller than the benchmark level if the off-street market is subsidised (0.8 per cent) and higher (0.27) if taxed. Given a high degree of substitution between the two markets, it is clear that off-street parking policy has an important effect on the magnitude of optimal on-street parking fees.

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of 5 km multiplied by 0.3 € per km) – see Table 11.1. Hence a tax of 20 per cent is equivalent to a parking fee of 0.3€.

[16] Calthrop (2001) considers a range of sensitivity tests on shares in different modes, shares in generalised prices and elasticities of substitution. As the results alter in essentially a predictable manner, and in the interests of brevity, we refer the reader to the original source.

V. Conclusions and suggestions for further research

Parking policies form a central part of urban transport policy in most cities. Yet surprisingly little economic evaluation of such intervention has been carried out. Our model highlights the elements that need to be considered in any policy assessment. Of central concern is the impact on reducing search externalities on the on-street market itself and the impact on (underpriced) road congestion. Both these elements have been stressed in the literature, although separately. Our model combines these elements and also points to potentially important effects on the off-street parking market and the rail market. A numerical model confirms the relative importance of distortions on secondary markets in determining efficient parking policies. For instance, were concern mistakenly restricted to the on-street market alone, the price would be set at less than one-half of the optimal benchmark-scenario rate. However, the results show that reforming on-street parking pricing may have significant impacts on parking search time, the effects on road-congestion levels are marginal.

We wish to stress several some important caveats in our research. We do this in the form of four suggestions for future research.

Empirical work

Though it is broadly agreed that urban transport authorities intervene in parking markets, little comparative work seems to be available on the different form this takes across cities and regions. For instance, we have been unable to find, in different cities, even basic information on, for instance: the on-street parking charge; the presence of time restrictions; the number of available spots; or, average search time required to find a vacant spot. Our numerical model also highlights the potential importance of the off-street parking market in determining optimal on-street prices. Yet we find little empirical evidence on the structure of the off-street parking market. Although some studies have been able to estimate the impact of parking fees on model choice (see Feeney (1989) for a slightly dated review), it is clear that there is scope for greater empirical work.

Micro-economics of search behaviour

At a theoretical level, the micro-economic underpinnings of search behaviour is poorly understood. This is potentially important. For instance, our model separates road congestion and search congestion. But in practice, the two aspects are likely to be highly correlated. Arnott and Rowse (2001) report that as much as one-half of downtown traffic is cruising for a vacant space. A better understanding of search behaviour is also necessary to evaluate information schemes. Should drivers be able to reserve downtown vacant spots? Can on-board technology be used to allow drivers to update reservations as new spots become available? How does information on parking availability on approaching freeways affect driver route choice? To keep models tractable, economists have tended to employ a reduced form approach in modelling search costs[17] either in a non-spatial or linear setting. One exception is Arnott and Rowse (2001), who use stochastic queueing theory to formulate a structural model, although this also requires relatively restrictive assumptions.

Enforcement

Most economic models assume that the government can freely set the on-street parking price. However, in the absence of enforcement, parkers may choose not to pay the meter fee. Yet enforcement is costly, and different levels of technology are available (traditional wardens, video-surveillance, barrier schemes etc). Several cities have recently contracted out enforcement to the private sector. While equation (9) can be considered as approximately holding for any given level of enforcement, welfare assessment needs to consider the optimal combination of parking fee and enforcement level. Fiscal federal considerations may also important in explaining observed government behaviour. For instance, the traditional regulatory framework in the U.K. allowed local government to set and keep meter fee revenues, while a regional police force set enforcement levels and the central government kept fine revenue payments. Local government had a clear incentive to set low meter fees in order to induce parkers to pay at the meter and thus prevent fine revenues flowing out of the locality.

Extending the range of instruments

This paper – in line with the economics literature – has considered the impact of altering the price of parking. However, urban policy involves a myriad of measures. A typical city may use a selection of parking instruments: the use of time restrictions to separate the long-and short-stay markets; altering the supply of on-street space; regulating the supply of off-street space; introducing park and ride schemes; giving local residents special parking rights; and banning parking from certain areas.

[17] Traffic engineers have made considerable efforts to model search behaviour at the micro-level. See Young (2000) for a review of the literature.

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Annex 1

Taking the total derivative of the indirect utility function, (8), gives:

$$\frac{dV}{dp_X} = \frac{\partial V}{\partial p_X} + \frac{\partial V}{\partial G}\frac{dG}{dp_X} + \frac{\partial V}{\partial \phi_F}\frac{d\phi_F}{dp_X} + \frac{\partial V}{\partial \phi_B}\frac{d\phi_B}{dp_X} + \frac{\partial V}{\partial \sigma}\frac{d\sigma}{dp_X} \tag{17}$$

Using Roy's rule and the definitions of the congestion function and search function, we know:

$$\begin{array}{ll}
\frac{\partial V}{\partial p_X} = -\lambda(T_{FX} + T_{BX}) & \frac{\partial V}{\partial G} = \lambda \\
\frac{\partial V}{\partial \phi_F} = -\mu(T_{FX} + T_{FY}) & \frac{\partial V}{\partial \phi_B} = -\mu(T_{BX} + T_{BY}) \\
\frac{\partial V}{\partial \sigma} = -\mu(T_{FX} + T_{BX}) &
\end{array} \tag{18}$$

Also note that:

$$\begin{array}{ll}
\frac{d\phi_F}{dp_X} = \phi_F'(\frac{dT_{FX}}{dp_X} + \frac{dT_{FY}}{dp_X}) & \frac{d\phi_B}{dp_X} = \phi_B'(\frac{dT_{BX}}{dp_X} + \frac{dT_{BY}}{dp_X}) \\
\frac{d\sigma}{dp_X} = \sigma'(\frac{dT_{FX}}{dp_X} + \frac{dT_{BX}}{dp_X}) &
\end{array} \tag{19}$$

Finally, revenue-neutrality implies, via equation (7) that:

$$\begin{aligned}
\frac{dG}{dp_X} = T_{FX} + T_{BX} + \tau(\frac{dT_{FX}}{dp_X} + \frac{dT_{FY}}{dp_X}) + p_X(\frac{dT_{FX}}{dp_X} + \frac{dT_{BX}}{dp_X}) + \\
(p_Y - m_Y)(\frac{dT_{FY}}{dp_X} + \frac{dT_{BY}}{dp_X}) + (f - \tilde{\theta}_R)\frac{dT_R}{dp_X}
\end{aligned} \tag{20}$$

Substituting equations (18),(19) and (20) into (17) gives expression (9).

FIGURES

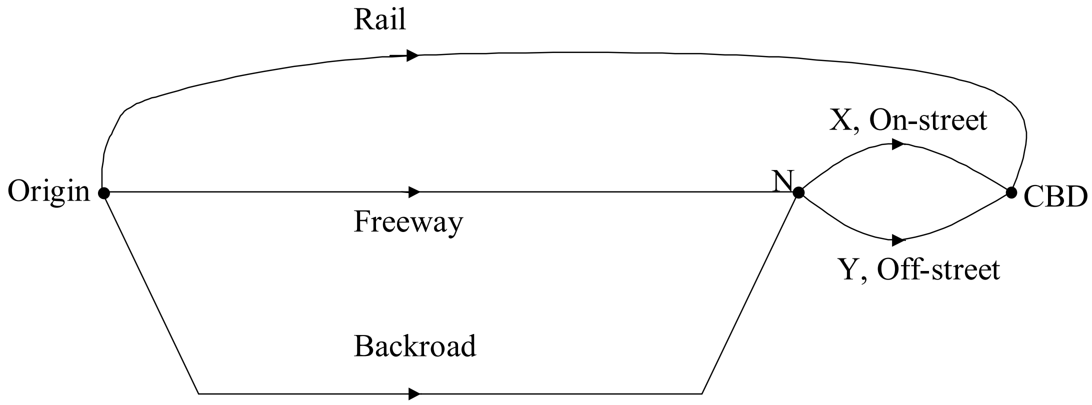

Figure 1 Network graph

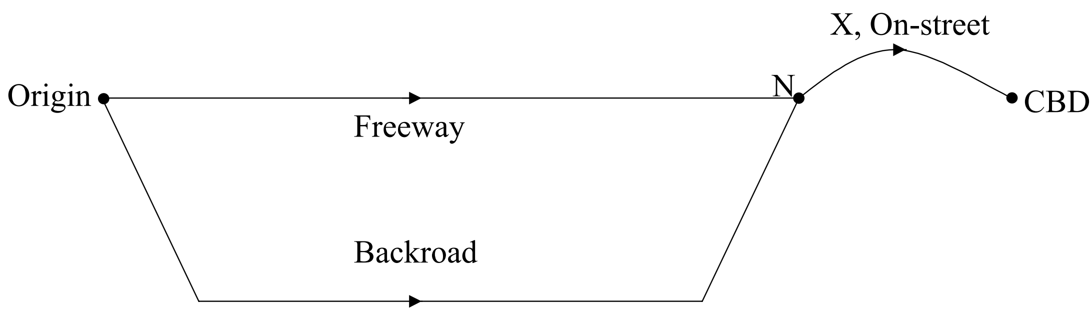

Figure 2 On-street parking only

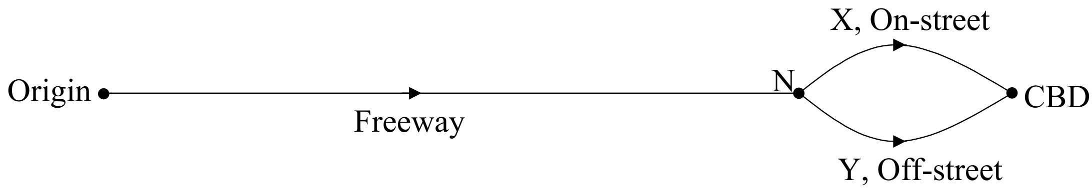

Figure 3 Single link

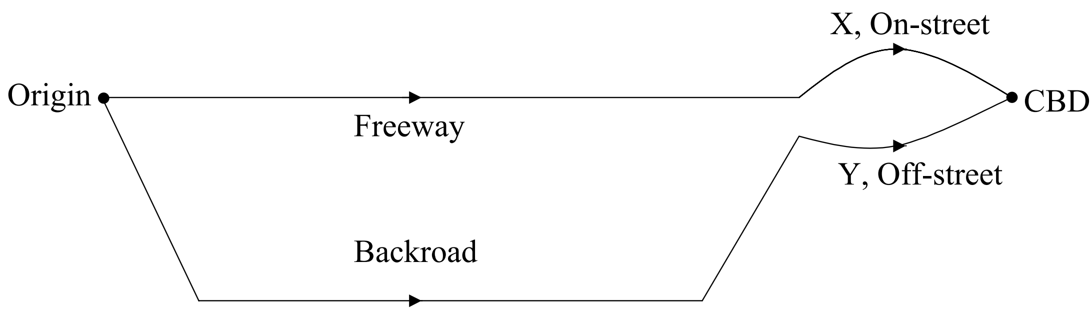

Figure 4 Separated parking markets

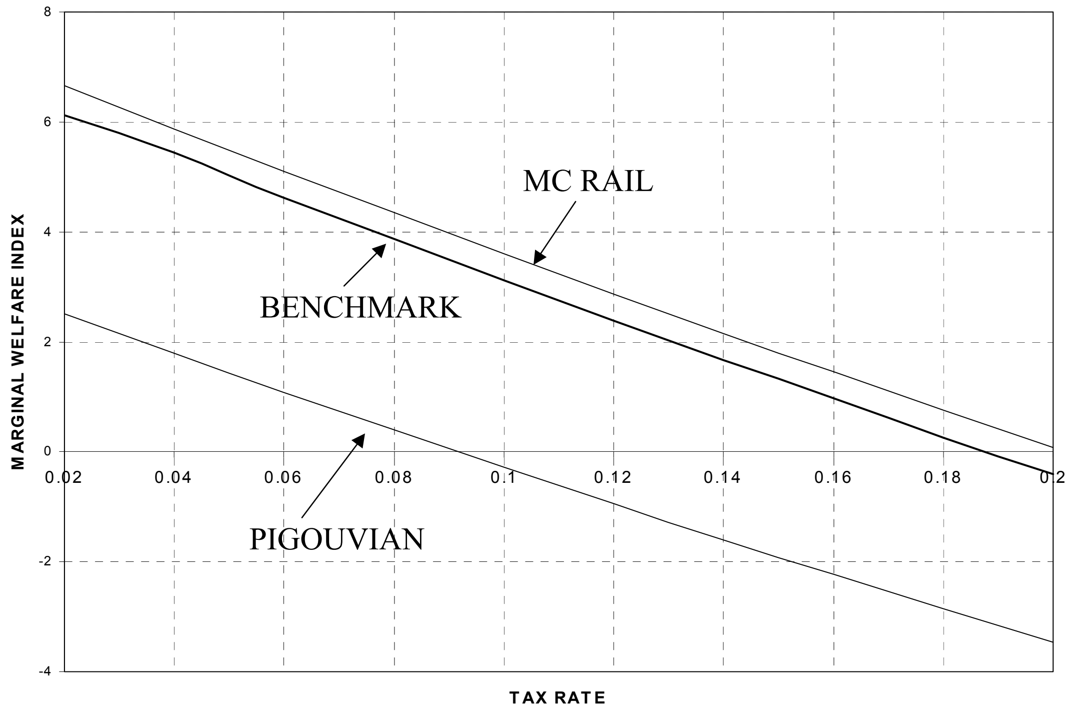

Figure 5 Benchmark model results

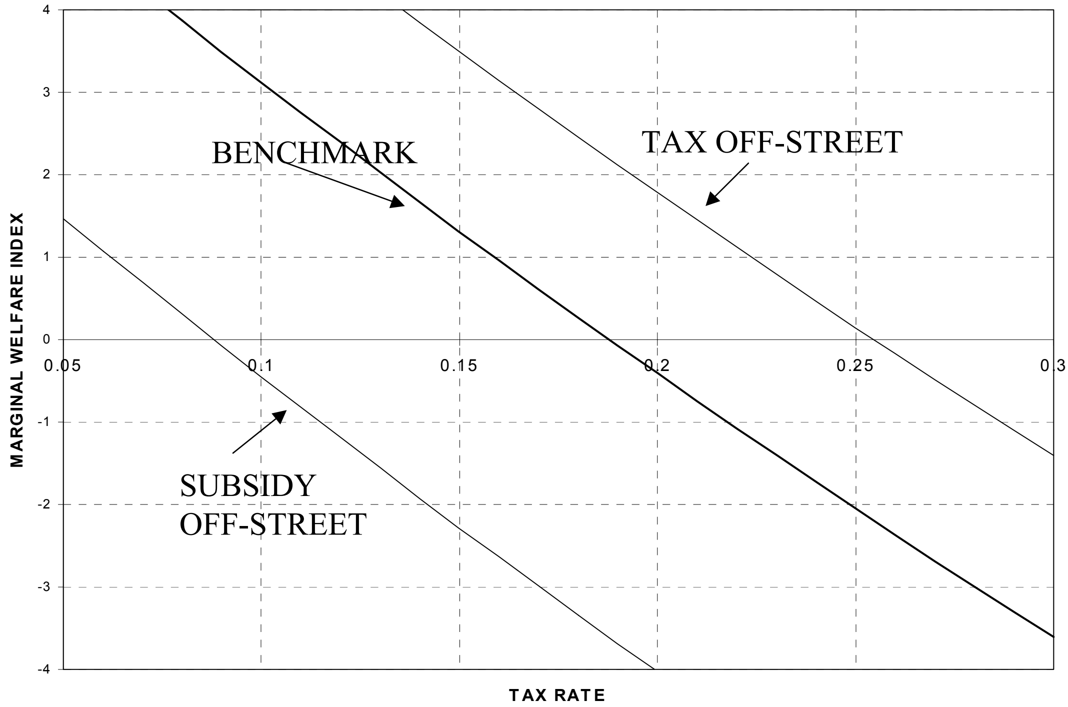

Figure 6 Sensitivity analysis: distortions on the off-street market

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