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Regulating urban parking space: the choice between meter fees and time restrictions*

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Abstract

On-street urban parking spaces are typically regulated by either a meter fee or a time restriction. This paper shows that, when the off-street parking market is perfectly competitive, meter fees are more efficient than time restrictions. When on-street parking is free, albeit subject to a time restriction, too many drivers choose to engage in socially wasteful searching for on-street spaces. In contrast, with a meter fee, the relative benefit of parking on-street is reduced, and total search costs can be minimised. A linear meter fee structure is shown to be optimal.

A simple policy prescription is also proposed. Set on-street meter fees equal to off-street parking fees. Finally, a simple numerical model calibrated to central London suggests that the use of optimal meter fees increases parking welfare by around 5% over an optimal time restriction.

1 Introduction

Politicians may prefer to regulate a market via a quantity control rather than a price control. Under a quantity control, a consumer can use the market for free, while under price regulation, she must pay a tax. In seeking election, politicians may be sensitive to the danger that a tax is perceived by the voter as a resource cost rather than a transfer. This choice of instrument is relevant to the urban parking market. Urban authorities must choose between regulation of on-street space via prices (a meter fee) or via quantity controls (a time restriction). Standard theory suggests that the choice of instrument (in the presence of lump-sum taxes and perfect information on benefit and cost curves) does not matter. Politicians may then opt for time restrictions in the hope of greater popularity.

We show that the choice of instrument in the parking market does matter. Furthermore, residents are better off if the politician adopts meter fees (and

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hands back the revenues) rather than time restrictions. Consider drivers arriving in the city centre at random during the peak period. Each driver must choose between searching for an on-street parking spot or driving directly to a privately-operated off-street parking complex. If on-street parking is free, albeit subject to a time restriction, whilst the off-street complex is subject to a fee, many drivers will engage in socially-wasteful searching activities for an on-street space. In contrast, an on-street meter fee reduces the relative attraction of on-street parking and results in smaller total search costs.

This simple point has not been made in the literature. Indeed, it is surprising how few papers have been written on parking, especially given the myriad of differing policies adopted by different urban authorities over time. Some authors concentrate on the use of parking pricing as a means to charge for road congestion externalities. Glazer and Niskanen [8] show that raising parking prices, by deterring trips to the city centre, may just encourage more through-traffic. Calthrop, Proost and Van Dender [5] use a numerical simulation model of Brussels to show that second-best pricing of all parking spaces produces higher welfare gains than a single-ring cordon scheme. Verhoef, Nijkamp and Rietveld [11] make a general case for using parking fees rather than supply constraints to internalize the external costs of road transport.

We are aware of only three papers that investigate the first-best regulation of on-street parking. Vickrey [12] makes the case, in a non-formal paper, for peak-load pricing of on-street space. He suggests a rule in which the price of remaining on-street spots is a function of the number of remaining unused spaces. Arnott, de Palma, and Lindsey [1] demonstrate that a spatially differentiated parking fee can reduce total travel costs in a bottleneck congestion model.

A recent paper by Arnott and Rowse [2] adopts an explicit representation of the stochasticity of vacant on-street parking spaces. Drivers decide upon which trips to make, whether to walk or drive, and, if driving, the distance from their destination at which to start searching for a vacant space. The model does not consider the off-street market nor the use of time restrictions. The central policy recommendation emerging from the model is that per time unit parking fees should be set equal to the value of the parking congestion externality: by parking for an additional unit of time, a driver reduces the mean density of vacant spaces and imposes additional travel time costs on all other drivers. However, the model exhibits multiple stable equilibria, which can be Pareto-ranked, but prevent the policy maker from being able to achieve the globally superior equilibrium with certainty. Moreover, the authors suggest that this result stems from the inherent complexity induced from uncertainty in the parking market.

We adopt a much simpler reduced-form representation of search costs. Although this lacks some of the sophistication captured by Arnott and Rowse, it contains the same basic mechanism: increasing on-street fees reduces the average duration of stay, thus increasing the mean density of vacant spaces and reducing the undesirable travel costs from searching. Furthermore, we integrate the private off-street market into our model, which alters the welfare message for efficient on-street pricing policy. We also analyse a commonly-used alternative to meter fees, namely time restrictions. When the off-street market is competitive, we show that on-street meter fees are more efficient than time restrictions. We also suggest a simple policy prescription: set meter fees equal to the off-street price.

Section 2 introduces our simple model of parking. Section 3 derives the centralized solution, while section 5 shows that meter fees can be used to perfectly decentralize the optimal allocation. Time restrictions, on the other hand, fail to do so. The analytical results of the paper are highlighted with a numerical example based on published data for central London, introduced in section 4. Section 6 concludes and emphasizes some directions of further work.

2 A simple model of urban parking

A fixed number, N, of identical risk-neutral drivers wish to park during the peak period in an urban centre. Each driver has a demand curve, or willingness-to-pay, for parking time given by $\alpha - \beta q$, where q denotes the quantity of time consumed. Parking spaces are provided on two separate markets. A fixed number of spaces are present on-street (market x). The fixed supply of peak-period hours of on-street parking is given by Q_x. Government regulates these spaces via either a per-time-unit meter fee or a time restriction. We assume perfect costless enforcement of these regulations: we comment on this assumption further in section 6. The opportunity cost of the on-street spots is assumed to be zero. In contrast, the private market provides off-street spaces (market y) under conditions of perfect competition at a per-time unit cost of C[1]. Finally, it is assumed that consumers are indifferent between parking on- or off-street[2].

The price for either market per time unit parked is denoted by $p_i \quad (i = x, y)$, and the resulting time consumed is given by $t_i(p_i) = (\alpha - p_i)/\beta$. A basic rationing problem arises if the fixed on-street supply is insufficient to meet demand (at a zero price): $Nt_x(0) = N\alpha/\beta > Q_x$.

In addition to choosing how long to park, each driver must choose whether to search for a space on the on-street market or use the off-street market. The assumed spatial layout of the problem is shown in Figure 1 . A driver approaches the urban area from point o, and must decide whether to turn left and proceed towards the on-street parking area x or turn right to the off-street area y. Travel

[1] On-street parking spots usually take up road space, and as such have a positive opportunity cost. However, we argue that some on-street parking spots cannot be converted into additional road-space in the short term e.g. a small stretch of road between two major junctions. Then the arguments in this paper would hold for those spaces alone. Secondly, even if all spaces had a positive opportunity cost, similar arguments would hold as long as this was less than the opportunity cost of off-street land, which seems likely.

[2] If expected consumer surplus from using either type of market is equal, we assume that drivers prefer to use the on-street market. This is just a resolution of an inequality and of no significance in what follows. The model can also be used to examine the case that on street spots are prefered to off-street or vice-versa. Given identical consumers, this amounts to adding a fixed cost to the use of one or other market. All expressions below would have to be altered for this new term.

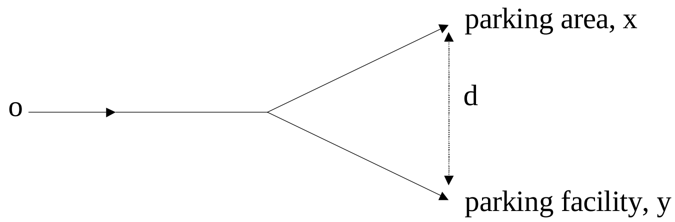

Figure 1: The spatial layout

costs from o to x and from o to y are identical and independent of the number of users i.e. there is no road congestion.

If she decides to proceed directly to the on-street area, x, but fails to find an available spot, she must return to the off-street area y. In doing so, however, she incurs a fixed driving cost penalty given by d. This formulation is a reduced form representation of a more complex spatial model of parking search costs. The model captures in a simple way an important relationship: better rationing of the on-street market will reduce the need for socially inefficient search/drive costs[3].

3 Centralized solution

Suppose that government could direct individual drivers to use a particular spot for a particular length of time (and that there are no other distortions in the economy). The government's problem is to maximize social welfare, W, given

[3]This is also the case in Arnott and Rowse [2] in which the expected cruse distance to find a space is given by $1/P$ where P gives the average density of vacant spaces.

However, in addition, consider a driver searching for a vacant space amongst Z spaces distributed equally at m metres apart. She begins at the off-street facility. Further the road is circular, so that after searching all Z spaces she returns to the off-street facility. For a probability ρ of a particular spot being vacant, the expected search distance is equal to:

$$\sum_{i=1}^{Z}\left[(1-\rho)^{i-1}\rho m i\right]$$

if the driver does not turn back (perhaps due to a one-way system). It can be shown that for large number of spaces, the expected driving costs falls as the probability of a spot being vacant rises. This is the relationship that is captured in a reduced form manner via the parameter d.

by the following function with respect to length of stay and number of users on each market (N_x denotes number of users of the x market):

$$\begin{aligned}
\underset{N_x,t_x,t_y}{Max}\ W &= N_x \int_0^{t_x} (\alpha - \beta q)dq + (N - N_x) \int_0^{t_y} (\alpha - \beta q - C)dq \qquad (1) \\
s.t. \quad N_x t_x &\leq Q_x \qquad (y_1) \\
N_x &\leq N \qquad (y_2) \\
N_x, t_x, t_y &\geq 0
\end{aligned}$$

where the expressions in brackets after the first two constraints give the respective multipliers. The necessary and sufficient conditions for the solution to the non-linear programme (1) are given by the standard Kuhn-Tucker conditions[4].

The optimal duration of stay on the off-street market, (when demand is positive), is equal to that induced by charging a per time unit price equal to the resource cost, C, i.e. $t_y^* = \frac{\alpha - C}{\beta}$. Assuming N_x and t_x are positive, the complementary slackness condition for time parked on the x market, requires that:

$$t_x^* = \frac{\alpha - y_1}{\beta} \qquad (2)$$

Substituting this information into the complementary slackness condition for the number of users of the x market, gives the following conditions:

$$\begin{aligned}
\left[\frac{(\alpha - y_1)^2 - (\alpha - C)^2}{2\beta}\right] - y_2 &= 0 \qquad (3a) \\
y_1 (Q_x - N_x t_x) &= 0 \qquad (3b) \\
y_2 (N - N_x) &= 0 \qquad (3c)
\end{aligned}$$

Three different solutions exist depending on the relative size of on-street supply, Q_x, the number of individuals, N, and the resource cost of off-street supply, C.

- $Q_x > N\frac{\alpha}{\beta}$

In this case, on-street supply is very large and there is no rationing problem. On-street supply is larger than parking demand at a zero price. The off-street market is not used. Drivers may park for as long as they wish. This is seen formally by noticing that $y_1^* = 0$ from condition 3b, and hence $y_2^* > 0$ from condition 3a, and $N_x^* = N$ from condition 3c.

[4] The constraints are linear, thus automatically satisfying constraint qualification. Further, it is straightforward to show that $W(.)$ is strictly concave and thus satisfies sufficiency.

- $N\frac{\alpha-C}{\beta} \leq Q_x \leq N\frac{\alpha}{\beta}$

Under this condition, on-street supply is too small to meet parking demand at a zero price. However, it is large enough to meet all demand at the efficient off-street price, C. The optimal solution just divides up the available on-street supply equally amongst all drivers. No-one uses the off-street market. This can be seen formally by noticing that when $y_1^* > 0$, condition 3b implies that $t_x^* = \frac{Q_x}{N_x}$. This can be used with equation 2 to solve for y_1^*, which when used in condition 3a implies that $y_2^* > 0$ and $N_x^* = N$. Condition 3a also shows that the optimal shadow cost of on-street supply, y_1^*, is smaller than the opportunity cost of off-street supply, C.

- $N\frac{\alpha-C}{\beta} > Q_x$

If on-street supply is relatively small compared to demand, particularly such that demand at the efficient off-street price cannot be met by on-street demand, the optimal price for on-street parking equals that off-street: $t_x^* = t_y^* = \frac{\alpha-C}{\beta}$. Further, only a fraction of drivers use the on-street market, the rest using the off-street market. This can be seen to be optimal by assuming that $N_x < N$, so that $y_2^* = 0$ from condition 3c, which in turn implies from condition 3a that $y_1^* = C$, and hence from 2 that $t_x^* = \frac{\alpha-C}{\beta}$. Condition 3b implies that $N_x^* = Q_x\frac{\beta}{\alpha-C} < N$ by assumption.

The third case, we argue, is the most realistic for large metropolitan areas in Europe. Demand for parking and the resource cost of urban land are relatively high, while the number of on-street parking spots is relatively low. The data for central London used in the numerical example supports the attention to the third case. We assume that this condition holds henceforth.

Consider the intuition for the result under the third case. The optimal length of stay is equal across both markets and equal to the stay induced by charging for the resource cost of off-street parking. Consider, instead, the situation in which drivers using the off-street market parked for the optimal length of time, t_y^*, whilst on-street parkers are induced to stay for a shorter time. More drivers can use the on-street spaces than under the optimal allocation. Now allow on-street parkers to park for a marginally longer period of time, such that one driver must transfer to the off-street market. Each remaining on-street parker can now park for a longer period, and hence their welfare increases. Furthermore, the driver that switches to the off-street market can also park for longer. The other off-street parkers are unaffected. Social welfare has increased. This reasoning applies as long as the duration of stay permitted on-street is less than or equal to that off-street.

Now consider the reverse case. Off-street parkers park for t_y^* units of time. On-street parkers, however, park for much longer, such that only relatively few drivers can use the on-street market compared with the optimal allocation. Consider marginally reducing the length of stay on-street, such that one driver can transfer from the off-street to the on-street market. The consumer surplus of the original on-street drivers falls, as each driver parks for a shorter duration.

However, given downward-sloping demand curves, the gain in consumer surplus to the driver that transfers from the off- to the on-street market is large enough to outweigh the losses to the original on-street parkers. Social welfare increases. This continues until on-street parking time is restricted to equal off-street.

We have restricted attention to the third case. The first case seems highly unrealistic, and, in any event, does not require any policy response. The second case may be relevant in some smaller urban areas, where low demand combined with a reasonable on-street supply may require a meter fee to ration all parking demand to on-street supply. This is the case studied in further detail by Arnott and Rowse [2]. We comment further on our model results under the second case in section 6.

4 Numerical Example

The discussion in this paper is illustrated with a simple numerical example, calibrated to data published on central London. Table 1 gives the base case values for parameters.

Table 1: base case parameter values

symbol	base case value	source
N	60,000	calculated from [5] [9]
Q_x	10,000*5	drawn from [9] [6] and [7]
α	20	assumed
β	4	estimated from[7] [9]
C	£ 5.15	drawn from [8] [4]
d	£ 2	assumed[9]

A few key parameters have no direct empirical counterpart and are thus assumed, notably the search cost parameter d. Sensitivity analysis of this parameter value is given below. Note also that the data supports the argument

[5] Using Figure 2 pp.16, we have estimates of the number of parking acts in central London per peak and off-peak period. Excluding the parking at the workplace, we sum combined parking acts by private cars and company cars. This is equivalent to 57,000 acts during the hours 0700-1300.

[6] Table 1 pp.17 reports that there were 11,355 meter spaces in central London in 1989. Elliot and Wright [5] report in Table 11 an equivalent figure of 14,390. We assume 10,000 spaces. We suspect that there is strong spatial variation in demand and supply within central London, although this is not reported in these sources. Hence we use a smaller estimate of the number of spaces and interpret our results as relating to those areas within central London in which demand is relatively high against supply.

[7] Figure 5 pp.17 excluding data relating to firm parking. However, no information is provided on price. Average duration is estimated at 4 hours. We assume a value of β equal to 4 such that if no price were charged, a driver would remain 5 hours.

[8] Table 3 pp.254 for City of London.

[9] There is some evidence to support the magnitude of this parameter. Axhausen [3] Figure 6 presents evidence from a study in Frankfurt that measured an average search time for an on-street space on a Saturday at 10.9 minutes. We would expect that the value of time spent searching for a space is higher than the in-vehicle travel time. If the value of time spent searching equals 10 pounds per hour, the value of the search for a space is approximately 2 pounds.

made in the previous section in favour of a relatively small on-street supply (case 3): $Q_x = 50,000 < N\frac{(\alpha - C)}{\beta} = 222,750$.

5 Decentralized solution

In practice, drivers choose whether to park off-street or attempt to park on-street. Government can only regulate the market subject to this selection constraint. Government typically must choose between one of two instruments: either a meter fee (m) or a time restriction (r). Under a time restriction, the driver parks for free, but must leave the spot within a pre-specified amount of time.

We only consider the case in which the off-street market is operated under conditions of perfect competition. The zero profit condition therefore implies that $p_y^* = C$. We make some further comments about the results under an imperfectly competitive off-street market in section 6 below.

5.1 Choice of destination and rationing rule

We assume that the probability of getting an on-street spot, ρ_x, is given by a simple random rationing rule[10]:

$$\rho_x(p_x) = \begin{cases} 1 & \text{if} \quad N_L(p_x)t_x(p_x) < Q_x \\ \frac{Q_x}{N_L t_x} & \text{otherwise} \end{cases} \tag{4}$$

where $N_L(p_x)$ gives the number of drivers attempting to park on the x market ('go Left'), later to be derived as a function of the price on-street. This particular rationing rule is most relevant to the situation in which each driver arrives at random over the peak period. Drivers cannot increase their probability of getting a spot by arriving earlier or later, or by using information on parking availability. The chosen representation captures in a simple way a key concern: the probability of a driver finding a spot is related to the length of time drivers would like to park for[11]. If per time unit prices are low, and drivers park for a relatively long period, the chance of any randomly arriving driver finding a

[10] This rule is referred to as a 'proportional-rationing rule' in Tirole [10] pp.213 or, when used to compute the expected demand curve, as a 'Beckmann-contingent' demand curve by Davidson and Deneckere [6].

[11] The representation is also consistent with stochastic queueing theory. The expected waiting time to gain entrance to a single server facility is given in a $M/D/1$ stochastic queueing model by:

$$W = \frac{t^2\lambda}{2(1-\lambda t)}$$

where λ denotes the arrival rate. It is straightforward to show that the expected queue time rises as the length of stay t rises. See Glazer and Niskanen [8] section 6 for a numerical example.

vacant on-street space is small. This representation is not suited to all types of parking markets - private workplace parking is often reserved, for instance.

Figure 2 illustrates the probability rule in the base case. The vertical axis shows price on the x market, p_x, while the horizontal axis gives the number of drivers attempting to park on-street, N_L. The shaded area shows (p_x, N_L) combinations which result in insufficient demand to meet on-street supply, and the probability of finding a vacant spot equals one. The non-shaded area to the right of the dividing line shows (p_x, N_L) combinations whereby demand exceeds supply and the probability falls below one. The dividing line plots the combinations for which demand equals supply: $\overline{N_L}(p_x) : \overline{N_L} = \beta Q_x / (\alpha - p_x)$. We have assumed that at $\overline{N_L}(C) < N$ (the third case from the dicussion in section 3 above). This implies that if the on-street price equals the off-street price, demand is greater than on-street supply.

Each driver decides whether to attempt to park on-street ('go left') or proceed directly to the off-street market ('go right'). Each driver is aware that failure to find an on-street spot will require driving back to the off-street market and thus incurring a cost d. For risk neutral drivers, the expected consumer surplus from going left is: $\rho_x CS_x + [1 - \rho_x][CS_y - d]$ where ρ_x is defined in equation (4), and CS_i gives the consumer surplus from parking on market i. If a driver goes right, she gains CS_y for certain.

Consider that on-street parking is free. Given that $\overline{N_L}(0) < \overline{N_L}(C) < N$, all drivers choose to go left $(N_L = N)$ if:

$$\frac{Q_x}{Nt^*(0)} CS_x(0) + \left(1 - \frac{Q_x}{Nt^*(0)}\right) [CS_y(C) - d] > CS_y(C)$$

which holds if:

$$\frac{Q_x}{N} > \frac{2\alpha d}{C [2\alpha - C] + 2\beta d} \tag{5}$$

Henceforth we assume that this condition holds, which is the case for our base-case parameter values. It implies that $N_L(0) = N$. Making this assumption eases exposition in the paper, but the results of this paper do not depend on this assumption: indeed, we give a sketch of the outcome when this condition fails to hold in the section 5 below. We return to the interpretation of this condition below.

We turn to the effect of meter fees on the choice to go left or right. Consider a strictly positive meter fee, $0 < p_{xm} < C$ (note the use of the second subscript to denote choice of regulatory instrument, $j = \{m, r\}$). Given the strict nature of the inequality constraint in (5), for a small enough increase in price, all drivers still attempt to park on-street. The increase in price causes each successful driver to park for a marginally shorter period of time, thus increasing the probability of finding a vacant on-street space. However, at the same time, the net gain in consumer surplus from finding a vacant space falls. Given the linear demand curves, the net effect on desirability of going left is negative - the net gain in expected consumer surplus from attempting to park on-street falls.

At a large enough meter fee, denoted by $p_{\underline{xm}}$, if all drivers go left, the expected gain in consumer surplus in successfully parking on-street exactly matches the expected search cost (the penalty cost of driving back to y) i.e. $\rho_x(p_{\underline{xm}})\, CS_x(p_{\underline{xm}}) + [1-\rho_x(p_{\underline{xm}})][CS_y - d] = CS_y$. Imagine that all drivers choose to go left at a price marginally above this level, $p_{xm} = p_{\underline{xm}} + \varepsilon < C$. Some drivers would do better by choosing to go directly to the off-street market. In (Nash) equilibrium, at this price level, only a subset of drivers attempt to park on-street ($N_{Lm} < N$).

Finally, consider a meter fee equal to the off-street price. The consumer surplus from parking on- and off-street is identical. In equilibrium, drivers will not choose left unless the probability of finding an on-street spot equals one. This gives the condition for the upper bound price, $p_{\overline{xm}}$: $N_{Lm}(p_{\overline{xm}}) = \overline{N_L}(p_{\overline{xm}})$. This is only fulfilled if $p_{\overline{xm}} = C$. If the price on-street is higher than off-street, all drivers will park directly off-street (go right). Therefore for $p_{xm} > p_y$, $N_{Lm} = 0$, and $\rho_x = 1$.

The number of drivers attempting to park on-street when meter fees are adopted is therefore either 0, N, or $N_{Lm}^{'}$ where:

$$N_{Lm}^{'}(p_{xm}) = \frac{Q_x}{2d}\left[\frac{(\alpha - p_{xm})^2 - (\alpha - C)^2 + 2\beta d}{(\alpha - p_{xm})}\right]$$

Hence we can write:

$$N_{Lm}(p_{xm}) = \begin{cases} N & \text{if} \quad p_x < p_{\underline{xm}} \\ N_{Lm}^{'} & \text{if} \quad p_{\overline{xm}} = C \geq p_x \geq p_{\underline{xm}} \\ 0 & \text{if} \quad p_x > p_{\overline{xm}} = C \end{cases} \tag{6}$$

Figure 2 shows the number of drivers going left under meter fees (a solid line). At prices less than $p_{\underline{xm}} = £3.09$ per hour, all drivers choose to go left: $N_{Lm}(p_{\underline{xm}}) = N = 60{,}000$. When the meter fee matches the off-street price, $p_{xm} = C = £5.15$, 22% of drivers choose left and the remainder go right.

The same types of conditions can be derived for the case of time restrictions, where the price per time unit, p_{xr}, gives the implicit price of the time restriction i.e. the price at which a driver would choose to park only for the duration of the time restriction. By assumption, at a zero price, equivalent to no time restriction, all drivers choose to go left (condition 5). In the case of a small implicit price (a long time restriction), it is clear that the consumer surplus from successfully parking on-street is greater than the case of meter fees. The net benefit to be traded off against the search cost is greater under time restrictions than meter fees. Given the assumptions made, all drivers continue to choose left even when the implicit on-street price matches the off-street price: $p_{xr} = C$.

Some attention is required in deriving the price at which only a subset of drivers choose to go left. Assuming that $\rho_x < 1$, we can derive a price, $p_{\underline{xr}}$, such that $N_L(p_{\underline{xr}}) = N$. If on-street supply is relatively small, such that

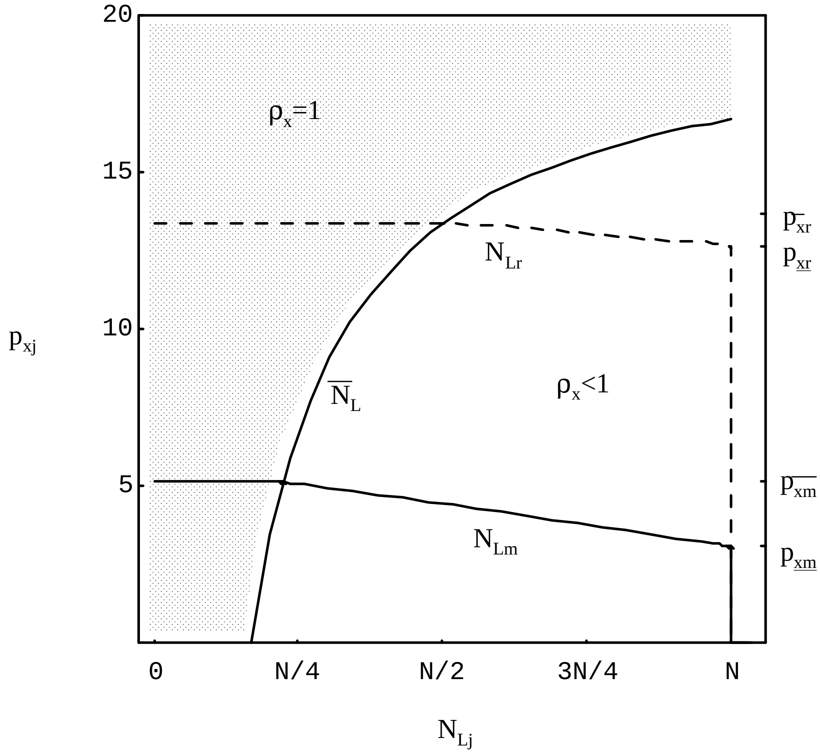

Figure 2: Number of individuals attempting to park on-street ("go left")

$\overline{N}_L(p_{\underline{xr}}) < N_L(p_{\underline{xr}}) = N$, then the assumption made about the probability is correct. Using the parallel definition for $p_{\overline{xr}}$ as in the case of meter fees, gives $p_{\overline{xr}} = \sqrt{C[2\alpha - C]}$, we can express the number of drivers choosing left as:

$$N_{Lr}(p_{xr}) = \begin{cases} N & \text{if} \quad p_{xr} < p_{\underline{xr}} \\ N'_{Lr} & \text{if} \quad p_{\overline{xr}} \geq p_{xr} \geq p_{\underline{xr}} \\ 0 & \text{if} \quad p_{xr} > p_{\overline{xr}} \end{cases} \tag{7}$$

where:

$$N'_{Lr}(p_{xr}) = \frac{Q_x}{2d}\left[\frac{(\alpha - p_{xr})(\alpha + p_{xr}) - (\alpha - C)^2 + 2\beta d}{(\alpha - p_{xr})}\right]$$

The base case has a relatively small on-street supply. Figure 2 depicts expression (7) as a dotted line. All drivers choose to attempt to park on-street at implicit prices up to £12.65 per hour (recall the price off-street is only £5.15 per hour). Even when the time restriction is such that drivers can park only a fraction of the time that they could park for off-street, drivers are better off parking for free on-street than paying the charge off-street. A fraction of drivers choose left and the remainder choose right at implicit prices between £12.65 to £13.39 per hour. At prices above this level, all drivers go right. Finally, note that on-street supply being 'relatively small' translates into the fact that at price $p_{\underline{xr}}$, $\overline{N}_L(p_{\underline{xr}}) \leq N_L(p_{\underline{xr}}) = N$.

Alternatively, on-street supply may be relatively large, such that $\overline{N}_L(p_{\underline{xr}}) > N_L(p_{\underline{xr}}) = N$. In this case, the original assumption that $\rho_x < 1$ is false at price $p_{\underline{xr}}$. Consider a price such that $\overline{N}_L(p_{xr}) < N$. All drivers choose to go left. This continues until the price that $\overline{N}_L(p_{xr}) = N$. At this point, the probability of finding a spot rises to one. All drivers continue to go left until the consumer surplus on-street exactly matches that off-street at $p_{\overline{xr}}$. At this price, all drivers are indifferent between parking markets. At a price above this level, all drivers choose to go directly to the off-street market.

Hence:

$$N_{Lr}(p_{xr}) = \begin{cases} N & \text{if} \quad p_{xr} \leq p_{\overline{xr}} \\ 0 & \text{if} \quad p_{xr} > p_{\overline{xr}} \end{cases} \tag{8}$$

The distinction between relatively large and relatively small on-street supply makes no difference to the basic result of this paper.

Finally, Figure 3 presents the inverse demand curve for on-street parking time under a meter fee (a solid line) and a time restriction (a dotted line) for the base case i.e. in which on-street supply is relatively small. On-street supply is shown as a solid horizontal line.

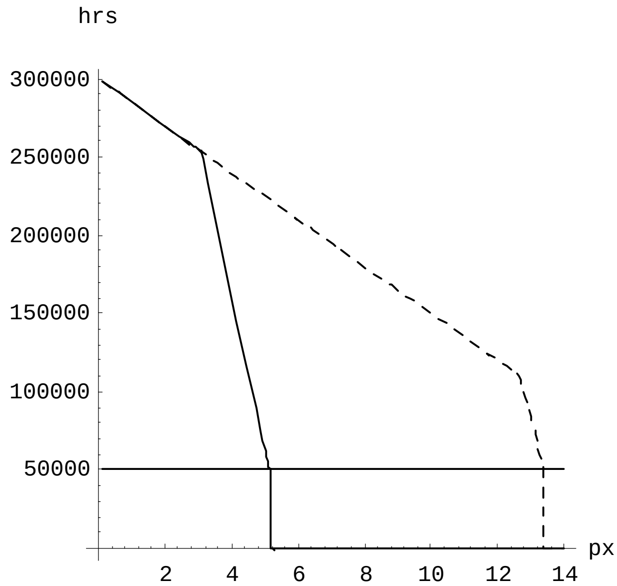

Figure 3: Inverse demand curve for on-street space

At relatively low on-street prices ($p_{xj} < p_{\underline{xm}}$), demand for on-street parking is identical under time restrictions or meter fees. All drivers choose left. In the interval $p_{\underline{xm}} = 3.09 < p_{xj} < p_{\overline{xr}} = 13.39$, however, demand for on-street parking is greater with a time restriction than a meter fee.

5.2 Optimal meter fees

The optimal meter fee can be read directly from Figure 2. At price $p_{xm} = C$, the number of individuals attempting to park on-street is such that the probability of finding a spot is one. Search-costs are eliminated. This replicates the first-best solution derived under the centralized solution. It is clear that welfare cannot be improved upon.

To see the result more formally, social welfare can be written as a function of p_{xm} alone.

$$EW_m(p_{xm}) = N_{Lm}(.)[\rho_x(.)SS_x(.) + [1 - \rho_x(.)][SS_y - d]] + [N - N_{Lm}(.)]SS_y \quad (9)$$

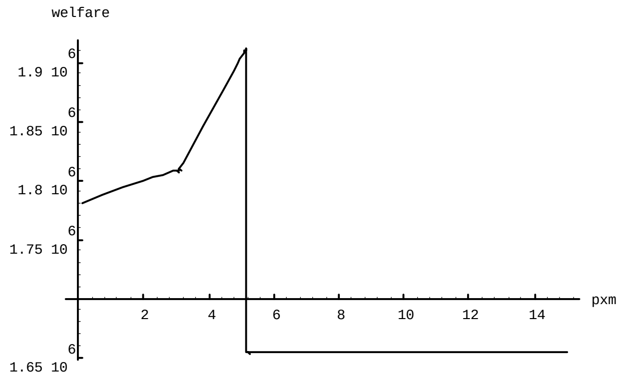

Figure 4: Social welfare with meter fees

where the social surplus on each market is given by SS_i:

$$SS_x(p_{xm}) = \frac{(\alpha - p_{xm})(\alpha + p_{xm})}{2\beta}$$
$$SS_y = \frac{(\alpha - C)^2}{2\beta}$$

and $N_{Lm}(p_{xm})$ is given by (6) and the probability of getting a spot, $\rho_x(p_{xm})$, by (4). Maximizing this non-continuous function with respect to meter fees results in Proposition 1.

Proposition 1 *When the off-street market in perfectly competitive, the optimal per time unit on-street meter fee, p^*_{xm}, is given by $p^*_{xm} = p_y = C$. Social welfare is identical to that with an optimal centralized solution.*

Proof. See Appendix ■

We have restricted attention to a linear per time unit on-street fee. However, given that this fee structure achieves the first-best outcome, it follows that a non-linear fee can do no better. We can therefore add a corollary:

Corollary 1 *When the off-street market is perfectly competitive, the optimal meter fee is linear.*

Figure 4 presents the social welfare function for the numerical example.

Consider a low price for on-street parking $p_x \leq \underline{p_{xm}} = £3.09 < C = £5.15$. With such a large price difference between the markets, all drivers attempt to park on-street: the net returns from successfully getting an on-street spot are sufficient to outweigh the search costs even if all drivers attempt to find a spot. As in the centralised solution, rationing benefits accrue from raising on-street prices as long as they are below the level off-street. However, in the presence of search costs, raising prices has an additional benefit: it reduces the number of drivers incurring the inefficient penalty cost, d, from having to return to the y market (alternatively, search costs fall). These two types of benefits accrue until the point $p_x = p_{\underline{xm}}$.

At a price marginally above this level $\left(p_x > p_{\underline{xm}}\right)$, only a fraction of drivers go left. A marginal increase in on-street fee, in addition to the previous two effects, also induces some extra drivers to proceed directly to the y market rather than to search on the on-street market. This results in an additional reduction in total search costs above those captured in the region $p_x \leq p_{\underline{xm}}$. .

Once $p_x > p_{\underline{xm}} = C$, all drivers choose to park directly on the off-street market. Marginally raising on-street fees has no effect. No-one uses the on-street space.

5.3 Optimal time restrictions

It is clear from Figure 2 that time restrictions cannot replicate the centralized solution. When prices are equal to the off-street level, all drivers choose to attempt to park on-street and total search costs are strictly positive. Time restrictions can be used to eliminate search costs in the base case by setting $p_{xr} = p_{\underline{xr}} > C$. But this price would lead to welfare losses from a badly rationed market (recall from the centralized solution, that setting prices above the level C lead to net rationing losses as too many people park for too short a time on-street). It turns out that the optimal time restriction is set between the level C and the price at which search costs are eliminated: the optimal restriction trades off the welfare losses from higher prices with the reduction in total search costs.

Social welfare can be written as a function of the implicit price of the time restriction p_{xr} alone.

$$EW_r(p_{xr}) = N_{Lr}(.)[\rho_x(.)SS_x(.) + [1-\rho_x(.)][SS_y - d]] + [N - N_{Lr}(.)]SS_y \tag{10}$$

where social surplus, SS_i, is defined in equation (9), $N_{Lr}(p_{xr})$ in equation (7) or (8) and $\rho_x(p_{xr})$ in (4). To simplify matters, we make a further assumption about on-street supply. We assume that:

$$\frac{Q_x}{N} < \frac{\left([\alpha - C]^2 - 2\beta b\right)^{\frac{1}{2}}}{\beta} \tag{11}$$

The restriction is met in the base case[12]. It ensures that at the optimal time restriction, on-street demand is greater than supply. We stress, however, that the main findings of this paper hold as long as $\frac{Q_x}{N} < \frac{\alpha - C}{\beta}$ (see discussion below

[12] $\frac{Q_x}{N} = 0.83 < \frac{\left([\alpha-C]^2-2\beta b\right)}{\beta} = 3.57.$

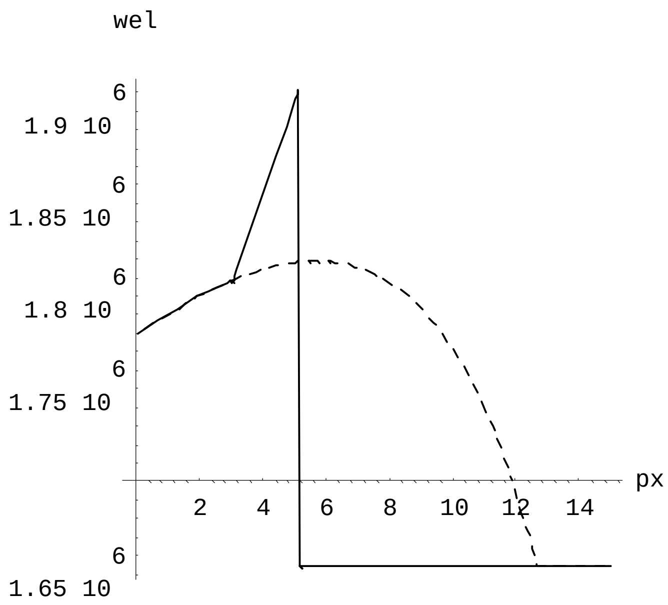

Figure 5: Social welfare under time restrictions and meter fees

at end of this section). The optimal level of time restriction is derived in the following lemma.

Lemma 1 *Given a perfectly competitive off-street parking market, and condition (11), the optimal implicit price of a time restriction, p^*_{xr}, is given by* $p^*_{xr} = \alpha - \sqrt{(\alpha - C)^2 - 2\beta d} > p^*_y = C$.

Proof See Appendix.

Figure 5 presents the social welfare function for time restrictions (the dotted line) imposed over that for meter fees (the solid line).

Consider first the case where the time restriction is much longer than the time chosen by the off-street users: $p_{xr} < C = 5.15$. All drivers select the on-street market. Marginally reducing the time restriction allows more drivers to park on-street generating net rationing benefits. Furthermore, less drivers incur the search cost d. Now consider $C < p_{xr} < \underline{p_{xr}}$. All drivers attempt to park on-street. Reducing the time restriction marginally will generate a net rationing loss ($p_{xr} > C$), but this is initially more than compensated for by the gain in welfare from reducing total search costs. An interior optimum exists at which the two opposing effects offset one another, at price p^*_{xr}. At prices marginally above this level, the loss of net rationing benefits outweighs the gain in reduced search costs. This continues until $p_{xr} = p_{\underline{xr}} = 12.65$. At a price above this level, some drivers switch directly to the y market thus saving the search cost. There is an additional marginal benefit from raising prices. It so happens that the net rationing loss from marginally raising prices is exactly offset by the combined reduction in search costs. The marginal benefit of raising prices is zero. Furthermore, this continues until $p_x = p_{\underline{xm}} = 13.39$ at which point the probability of getting an on-street spot is one. Raising on-street prices above this level has no impact as all drivers park off-street.

This discussion relates to the base case in which on-street supply is 'relatively small'. As shown in the proof of Lemma 1, however, the same result holds for the case in which on-street supply is relatively large, although the shape of the welfare function is slightly altered. The central result of this paper is collected in Proposition 2.

Proposition 2 *Given a competitive off-street market, social welfare is lower in the case that government adopts an optimal time restriction to regulate the urban on-street parking than in the case with an optimal (linear) meter fee. Furthermore, the net loss in welfare from adopting a time restriction is increasing in the search cost parameter d.*

Proof. See Appendix ■

This Proposition follows directly from Proposition 1 and Lemma 1. It is also intuitive. The difference between the efficiency of the two instruments stems from the impact on searching behaviour. If there are no search costs ($d = 0$), the two instruments are identical (although trivially $N_{Lr} > N_{Lm}$). Table 2 reports some sensitivity analysis on the value of parameter d, which illustrate the finding of the Proposition.

Table 2

	j	p^*_{xj}	$p_{\underline{xj}}$	$p_{\overline{xj}}$	ρ^*_x	W
$d = 1.5$	m	5.15	3.65	5.15	1	100
	r	5.56	12.88	13.39	0.230	96.36
$d = 2.0$	m	5.15	3.09	5.15	1	100
	r	5.70	12.65	13.39	0.233	95.16
$d = 2.5$	m	5.15	2.54	5.15	1	100
	r	5.84	12.40	13.39	0.235	93.95

The table considers three scenarios for parameter d: a low value, $d = 1.5$, the base case value, $d = 2$, and a high value, $d = 2.5$. This can be thought of as sensitivity tests on the value of time whilst engaged in searching activities. The performance of both instruments are considered under each scenario. First notice that the welfare level W achieved under meter fees is independent of the search cost parameter. This is obvious as there is no searching in the optimum. However, under time restrictions, welfare declines as d increases.

Secondly, note that the optimal implicit price for the time restriction increases in d. As search costs become more important, the marginal benefits from increasing prices above C rise, whilst the marginal cost - the loss in net rationing benefits - stays constant. The optimal price increases; alternatively, the optimal time restriction is shorter the greater the distress caused from searching behaviour. The optimal meter fee, by contrast, is independent of d. At that price only the number of drivers will choose to attempt to park on-street such that the probability of finding a spot is one. Search costs are not relevant.

Thirdly, note that under either instrument choice, $\underline{p_{xj}}$ is declining in parameter d. For any given price on-street, the net gains from successfully finding an on-street spot are offset ever more rapidly by the rising search costs if all drivers choose left. The price at which only a subset of drivers can search is lower the higher the search cost. In contrast, $\overline{p_{xj}}$ is independent of the level of d for either instrument. At this price, the net gain from being able to park on-street is zero and sufficient drivers go left such that the probability of finding a spot is one. This condition is not dependent on the search cost parameter.

Finally, note that in the optimum, the probability of finding a spot with meter fees is one, whilst for time restrictions is around 0.23, although this is slightly rising in the parameter d.

Expressions (11) and (5) restrict the size of on-street supply. Infact, the basic result of the model holds under a more general restriction: $0 < Q_x/N < (\alpha - C)/\beta$. Consider first the case in which restriction (5) does not hold: on-street supply is extremely small. At a zero price, the probability of finding a spot is so low that not all drivers would choose to go left. The number of drivers choosing left would fall from $N_{Lj}(0) < N$ to $N_{Lm}(C) = \overline{N}_{Lm}(C)$ in the case of meter fees. The price $\underline{p_{xm}}$ does not exist. Under time restrictions, the demand curve would bend-backwards: $N_{Lr}(p_{xr})$ would initially be increasing in p_{xr} only to decrease beyond a certain point. The price $\underline{p_{xr}}$ might have two solutions or none. Proposition 1 holds as meter fees can still reproduce the centralized solution. However, the form of the optimal time restriction given in Lemma 1 would change, although the basic inferiority of time restrictions remains.

Finally, consider the case in which on-street supply fails to meet (11). On-street supply is very large. Proposition 1 still holds. The optimal time restriction given in Lemma 1, however, lies at a price for which the probability of finding an on-street spot is one. Lemma 1 can no longer hold: $\overline{N}_L(p^*_{xr}) > N$, which is not optimal. Instead it is optimal to raise the implicit price up until the price at which $\overline{N}_L(p_{xr}) = N$. Again, the form of the optimal time restriction given in Lemma 1 alters, but the basic inferiority result remains.

6 Conclusion

In practice, time restrictions are a popular instrument for regulating urban on-street parking. This paper has shown that, as long as the off-street market is relatively competitive, time restrictions may induce too much wasteful searching. Linear meter fees, in contrast, can solve the allocation problem efficiently. The greater the search problem, the relatively better it becomes to adopt meter fees rather than time restrictions. These results are collected together in Propositions 1 and 2 of the paper.

Deriving strong policy prescriptions from such a simple model warrants a number of caveats. Firstly, the result only holds for a perfectly competitive off-street market. Indeed, for the case of an off-street monopolist, the model can be used to show that time restrictions can perform equally well as meter fees. When off-street prices are high relative to resource cost, government can set meter fees higher than level C. At the margin, raising prices induce less drivers to have to use the distorted off-street market and reduces total search costs. However, the optimal meter fee will typically be at a level in which all drivers choose left. Therefore both time restrictions and meter fees will be identical.

Secondly, the model assumes identical individuals. We think that in a more complicated model, with consumer heterogeneity, a similar result will emerge: the model result is driven by the difference in consumer surplus between a quantity and price instrument.

Thirdly, as noted above, the random rationing rule ignores potentially important margins of driver behaviour that can be used to influence the probability of getting a spot. For instance, some drivers may arrive earlier, thus substituting schedule delay costs for reduced expected search costs. Alternatively, drivers may be able to engage in some costly activity to acquire greater information on parking availability. As a result, the model is probably best suited to study parking policies for urban areas concentrating on retail and leisure activities (rather than non-retail employment centres).

Fourthly, we assume that on-street supply is sufficiently small that the third case in section 3 is relevant rather than the second case. We argued above that the third case is most relevant to large urban areas. Under the second case, all peak period parking demand is efficiently allocated to the on-street market. The off-street market is not used. An on-street time restriction or a meter fee are equivalent as the probability of finding a spot is equal to one.

Fifthly, we have abstracted from issues to do with enforcement of on-street parking. Enforcing any on-street price is costly: if no enforcement is used, drivers will choose to park illegally. The expression for the optimal on-street fee will reflect this cost. As noted by Elliot and Wright [7], the decision to park illegally may slow down the parking warden, by requiring the writing of a ticket. This lowers the probability of being caught for other drivers. This type of externality may be important.

Finally, we ignore potential consequences from the fact that parking decisions are the domain of urban governments. Incentives may exist to raise revenue from non-voting drivers (such as long-distance commuters or tourists), or to over-invest in enforcement to capture meter fee revenues rather than risk losing fine revenues to the central government.

This suggests that an important research agenda remains in determining better parking policies.

7 Appendix

This Appendix contains the proofs of the Propositions and Lemmas contained in the paper.

7.1 Proof of Proposition 1.

Begin with $p_{xm} < p_{\underline{xm}}$, where $p_{\underline{xm}} > 0$ by the 'greater-than' condition in (5). The marginal benefit of raising the on-street price is given by the derivative of [9], whilst noting that by definition $N_{Lm} = N$ and $\rho_x < 1$:

$$EW_m^{'} = \frac{Q_x}{2}\left[1 - \frac{\left((\alpha - C)^2 - 2\beta d\right)}{(\alpha - p_{xm})^2}\right] \tag{12}$$

This marginal benefit function is strictly positive for $0 < p_{xm} \leq p_{\underline{xm}}$ if $p_{\underline{xm}} < C$. Deriving the explicit solution for $p_{\underline{xm}}$, it is clear that $p_{\underline{xm}} < C$ if $Q_x/N < \frac{\alpha - C}{\beta}$ which is the case by assumption. It can be shown that the welfare function is continuous at the point $p_{\underline{xm}}$.

Consider the marginal increase in welfare of raising p_{xm} when $p_{\underline{xm}} \leq p_{xm} \leq p_{\overline{xm}} = C$. Using (9), substituting for $N_{Lm} = N_{Lm}^{\prime}$, this is given by the expression:

$$EW_m^{'} = Q_x > 0$$

Finally, consider $p_{xm} > p_{\overline{xm}}$. (note that the welfare function is discontinuous at the point $p_{\overline{xm}}$). It is clear that the marginal benefit of further increasing prices is zero $\left(EW_m^{'} = 0\right)$. Given the discontinuous nature of the welfare function at $p_{xm} = p_{\overline{xm}}$, it remains to compare $EW_m(p_{\overline{xm}})$ with $EW_m(p_{\overline{xm}} + \varepsilon)$. Using expression (9), it is direct to show that $EW_m(p_{\overline{xm}}) > EW_m(p_{\overline{xm}} + \varepsilon)$. Hence the optimal level of on-street prices is given by $p_{xm}^* = \overline{p_{xm}} = C = p_{y.}^*$ All model variables are identical to the centralized solution. QED.

7.2 Proof of Lemma 1.

This proof follows the structure of the proof of Proposition 1. By virtue of the greater-than condition in expression (5), $p_{\underline{xr}} > 0$, and, further, it can be shown that $p_{\underline{xr}} > C$ if $\alpha > C$ as assumed. Consider $p_x < p_{\underline{xr}}$. Further, we begin with the case that on-street capacity is relatively small $(\overline{N}_L(p_{\underline{xr}}) < N_L(p_{\underline{xr}}) = N)$.

The marginal benefit of raising the implicit price (lowering the time restriction) is given by equation (12). An interior local optimum exists at $\widehat{p_{xr}} = \alpha - \sqrt{(\alpha - C)^2 - 2\beta d}$ if $\widehat{p_{xr}} < p_{\underline{xr}}$. This follows from assumption (5)[13].

Now consider the marginal increase in welfare of raising p_x when $p_{\underline{xr}} \leq p_x \leq p_{\overline{xr}}$. Taking the derivative of [10] gives that $EW_r^{'} = 0$. The benefits from reduced search costs (both via inducing less drivers to attempt to park

[13] Although the greater-than condition on on-street supply is required to ensure $\widehat{p_{xr}} < p_{\underline{xr}}$, this can be relaxed. See discussion at end of section 5.

on-street and by reducing the number of drivers that attempt but fail to find a spot) exactly offset the loss in welfare from over-use of the on-street market. The net marginal effect is zero. Finally, if $p_x > p_{\overline{xr}}$, no drivers use the x market. The impact of a marginal increase in the implicit price of parking is therefore zero. Moreover, it can be shown that the social welfare function is continuous. This implies that the globally optimal solution is given by $p^*_{xr} = \alpha - \sqrt{(\alpha - C)^2 - 2\beta d}$.

Consider the relatively large capacity of on-street supply: $\overline{N}_L(p_{\underline{xr}}) > N_L(p_{\underline{xr}}) = N$. On-street supply meets all on-street demand at price $\widetilde{p} : \overline{N}_L(\widetilde{p}) = N$. For price $p_x \leq \widetilde{p}$, the marginal welfare from raising prices is given by expression (12). A local optimum exists if $\widehat{p_{xr}} < \widetilde{p}$, which substitution of terms reveals must hold by virtue of condition $\frac{Q_x}{N} < \frac{\left([\alpha - C]^2 - 2\beta d\right)^{\frac{1}{2}}}{\beta}$ from expression (11). Note that the social welfare function is continuous at point $\widetilde{p}$.

For $p_x > \widetilde{p}$, the marginal benefit of raising prices further is negative: $\frac{\delta}{\delta p_x}[N * SS_x] = \frac{-Np_x}{\beta} < 0$. The marginal benefit of raising prices above the point $p_{\overline{xr}}$ is clearly zero as for the small capacity case. The social welfare function can also be shown to be continuous at that point. Hence the globally optimal price is given by $p^*_{xr} = \alpha - \sqrt{(\alpha - C)^2 - 2\beta d}$. Further, this holds for the case of relatively large and relatively small on-street capacity. QED.

7.3 Proof of Proposition 2.

First, we prove that social welfare is lower than that achieved with either an optimal meter fee or a centralized solution. Substituting the optimal values for p^*_{xm} and p^*_{xr} into their respective social welfare functions reveals:

$$SW_m - SW_r = Nd - Q_x(\widehat{p_{xr}} - C) \tag{13}$$

This is strictly positive if:

$$\frac{Q_x}{N} < \frac{d}{(\widehat{p_{xr}} - C)} \tag{14}$$

But substitution of terms reveals:

$$\frac{\left([\alpha - C]^2 - 2\beta d\right)^{\frac{1}{2}}}{\beta} < \frac{d}{(\widehat{p_{xr}} - C)}$$

and hence (14) is satisfied by condition (11). Hence (13) > 0.

Second, we prove that the gain in welfare from using meter fees rather than time restrictions is increasing in parameter d. The derivative of (13) with respect to d is strictly positive once condition (11) is satisfied. QED.

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