Spatial Competition between Parking Garages
and
Downtown Parking Policy

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This paper looks at parking policy in dense urban districts ("downtown"), where spatial competition between parking garages is a key feature. The paper has four parts. The first looks at the "parking garage operator's problem". The second derives the equilibrium in the parking garage market when there is no on-street parking, compares the equilibrium to the social optimum, and examines parking policy in this context. The third considers how the presence of on-street parking alters the analysis, and the fourth extends the analysis to include mass transit.

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1. Introduction

Urban transport economists have recently been giving more attention to the role of parking in the management of urban auto congestion. No paper in the current literature concentrates on parking garages, which are a key element in the parking picture for central business and commercial districts[2]. The principal aim of the paper is to fill this gap. The paper first presents an economic model of a parking garage, then derives a spatial competition equilibrium between parking garages, and then enriches the model to include on-street parking and mass transit. Aspects of parking policy are discussed for each of the model variants.

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[1] Some of the material in this paper was developed in conjunction with Arnott, Tilmann, and Schöb (2005), and in conjunction with Arnott and Rowse (2005). I would like to thank my co-authors for their collaboration. I would also like to thank Liza Cheviakhova for preparation of the diagrams, and for helpful comments on an earlier draft of the paper.

[2] Calthrop (2001) presents a model in which off-street parking is provided at constant cost, and considers the case where the off-street parking provider has monopoly power. Many of the results he obtains are qualitatively similar to ours. In some respects, his model is more general; notably, he allows for car and mass transit travel to be imperfect substitutes. The major difference between the two approaches is that the modeling approach in this paper is more "structural", so that equilibrium in the parking garage market is derived from the technology of garage construction and the game between parking garages.

Arnott, Tilmann, and Schöb (2005), Ch.2, too covers much the same ground as this paper, but its emphasis and its treatment of parking garages is different. It puts the spotlight on cruising for parking, and discusses some issues raised by driver heterogeneity. Also, its treatment of parking garages is similar to Calthrop's, except that it has an upward-sloping marginal cost curve for off-street parking, and assumes that the equilibrium off-street parking fee is a weighted average of the competitive and monopoly prices.

An essential feature of parking garages is that they exhibit *horizontal* economies of scale, at least over an initial range, since the central ramp entails a fixed cost. As a result, parking garages are not provided continuously over space but instead at discrete intervals. A driver is willing to pay a premium to park in a garage that is closer to his destination since doing so reduces his walking time costs, which gives private parking garage operators market power. This effect should be taken into account in the design of parking policy. The local transportation authority may choose to influence private garages' pricing and capacity choices through taxation and/or regulation, or to construct and/or operate parking garages itself. But also the local transportation authority should take into account how private garage operators will respond to other aspects of urban transport policy, including on-street parking and mass transit pricing.

The model is tailored to treat traffic congestion and parking in high-density, heavily-congested areas of a city, particularly the central business and commercial districts, such as downtown Boston (as defined in Boston Transportation Department (2001)). In 1997/8 downtown Boston had 40500 parking spaces within an area of 1.4 square miles. Let us suppose, for the sake of argument, that a parking space occupies 400 square feet. If all parking were on street, it would take up 41% of the land area. In conditions of such high density, parking garages are the dominant source of parking supply.

The paper has four parts. The first looks at the "parking garage operator's problem". The second derives equilibrium in the parking garage market when there is no on-street parking, and examines public policy in this context. The third considers how the presence of on-street parking alters the analysis. And the fourth adds mass transit.

2. *The Parking Garage Operator's Problem*

One can envisage an urban economy where, in dense urban districts, parking is continuously distributed over off-street space; each building might have the ground floor, or one or two underground floors allocated to parking, for instance. But this is not normally observed; instead, parking garages are spaced at discrete intervals. The primary reason is the technology of constructing parking garages. As noted in the introduction, the fixed space needed for a circular parking ramp results in horizontal economies of scale. As well, because parking garages are such particular structures, it is cheaper to construct one building that is exclusively devoted to parking and other buildings that are devoted to non-parking uses than to construct buildings with some of the space allocated to parking[3]. A secondary reason is land use controls. Parking garages are by their nature unsightly (though this can be mitigated by attractive architecture) and can generate traffic problems. For these reasons, land use controls often restrict their location, size, and height. In what follows, we shall abstract from all these considerations except for the horizontal economies of scale intrinsic to parking garage construction technology.

[3] Garage construction costs would probably be quite reasonable if the ground floor of a building were allocated to parking, but this space is especially valuable in retail use.

In this section and the next, we shall investigate the nature of the spatial equilibrium that arises in an otherwise isotropic (spatially uniform) downtown area in the presence of these economies of scale. Garages will be located at discrete intervals from one another; due to walking costs, garage operators will have market power, and will exploit this by pricing above marginal cost. There will also be strategic interaction between parking garages; when deciding where to locate, how large a parking structure to build, and what pricing structure to adopt, a garage operator will attempt to anticipate the reactions of his competitors, the neighboring parking garages. How should the game between the parking garages be modeled?

One obvious consideration is that parking garages compete in space. There is a large and well-developed literature on games of spatial competition (a brief survey is presented in Tirole (1988)), and the parking garage game should build on this literature. Each garage has a well-defined set of nearest neighbors, with which it competes directly. A customer will choose to park in that garage with the lowest full price, where the full price equals the garage fee plus the walking costs from the parking garage to the destination and back again. Another important consideration is that, once a parking garage is built, it is very costly to alter its capacity, and prohibitively costly to alter its location. Accordingly, the most natural way to model the game between parking garages is as a repeated, two-stage sequential entry, spatial competition game, with demand growing over time. Each period, in the second stage of the game, incumbent garages compete in fee schedules, taking as given the location and capacity of other parking garages. A garage will take into account that if it raises its fee schedule, its neighboring garages will be able to accommodate the diverted customers only to the extent of their excess capacity; and similarly, if it lowers its fee schedule it can absorb the extra customers generated only to the extent of its own excess capacity. Thus, capacity constraints will play an important role, and equilibrium (if it exists[4]) will entail excess capacity. In the second stage of the game, based on expectations concerning future demand, potential entrants decide simultaneously whether to enter, and conditional on entry where to locate and how much capacity to build (Prescott and Visscher (1977)). .

This specification of the parking garage game is natural. Unfortunately, it is also complicated. A broader model of downtown parking and traffic congestion that incorporated this parking garage game module would be cumbersome. As a result, we have decided to adopt a simpler but also less realistic specification of the parking garage game.

The model will be familiar to all students of spatial competition theory[5]. Space is isotropic/homogeneous – a circle or an unbounded line in one dimension, or the surface

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[4] Each garage will recognize that as it raises its fee schedule, it will lose more and more customers, but that eventually the neighboring parking garages may become full, in which case it will not lose any more customers by further raising its fee schedule. This casual argument suggests that a garage's profit function is not in general concave in the parking fee, which leads to problems of non-existence of a pure strategy Nash equilibrium. If a pure strategy Nash equilibrium does not exist, there may nonetheless exist an equilibrium in which garages play mixed strategies.

[5] I do not know the provenance of the game. Tirole (1988) presents it as due to Salop (1979). But Salop (1979) dressed up in then-modern garb an older model, which is presented in Vickrey's masterly overview of spatial competition theory in his *Microstatics*(1964, reprinted as Vickrey, Anderson, and Braid (1999)) that anticipated most modern developments. The older model refers to the assumption that each firm, when deciding its price, takes its neighbors' locations and prices as fixed as "zero price

of a sphere or a homogeneous plain in two dimensions. The game between spatial competitors has two stages. There are no capacity constraints, and demand is inelastic and uniform over the space. In the second stage, each firm chooses its price, taking as given the locations and prices of its immediate neighboring firms, which are assumed to be arrayed symmetrically and to have the same prices; in doing so, it trades off a higher profit per unit sold with a higher price against a reduced market area. Then symmetry is imposed. This generates an equilibrium price as a function of the spacing between firms. In the second stage of the game, entry and exit result (the mechanism is unspecified) in the spacing between firms being such that zero profits are made. We refer to this game as the *spatial competition game*, and the corresponding equilibrium as the *spatial competition equilibrium*.

In this section, we derive a garage's price reaction function of the second-stage game, and the implied capacity choice, as "the parking garage operator's problem". And in the next section, we derive the Nash equilibrium of the game, and compare this equilibrium with the corresponding social optimum.

We now turn to the parking garage operator's problem, in which one garage, labeled garage 0, chooses the profit-maximizing garage fee to charge, taking as given the symmetric location and prices of neighboring garages

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and locational conjectural variations". In modern terminology, what is being solved for is the sub-game perfect Nash equilibrium of a two-stage game, with prices being determined in the second stage, and locations in the first.

We shall employ the following notation:

T	parking duration
Π	parking garage 0's profit per unit time
k	capacity of garage 0 (number of parking spaces)
h	height of parking garage 0 (number of storeys)
r	land rent
C(k,h;r)	(flow) costs of parking garage 0
x	distance from parking garage 0
S	parking fee per unit time charged by other parking garages
S_0	parking fee per unit time charged by garage 0
b	grid distance to the boundary of garage 0's market area
d	grid distance between parking garages
$D(x,S_0;S,d)$	garage 0's demand (flow rate of new parkers) per unit area at x
M	market area of the parking garage
w	walking speed
v	value of time
A	land area of parking garage

To simplify, we assume that all customers park for the same length of time[6], T, and that there is a grid road network so that a garage's market area is diamond shaped. Under the maintained assumption that the garage operates at full capacity, the parking garage operator's profit function is

$$\Pi = S_0 k - C(k,h;r) \qquad \text{s.t.} \qquad k = T \int_M D(x,S_0;S,d)\, 4x\, dx. \qquad (1)$$

Profit per unit time equals the fee per unit time, S_0, times the number of parking spaces in the parking garage, k, minus garage costs, C(k,h,r), where h is the number of storeys in the parking garage and r is land rent. The constraint specifies that the number of parking spaces equals the integral of demand for parking spaces per unit area, D (which depends on the distance from the parking garage, x, the garage's fee, the fee charged by all other garages, S, and the spacing between parking garages, d), over the garage's market area,

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[6] It would be more natural to assume that visit rather than parking duration is exogenous, but then the garage operator could infer from a customer's parking duration how far his destination is from the parking garage, and would have an incentive to price discriminate on that basis. We wish to avoid this artificial complication.

M (the market area between x and x + dx is 4x dx). Viewing the constraint as a function relating price to capacity, $S_0 = S_0(k;S,d)$, one obtains the familiar first-order profit-maximization condition that parking spaces should be added up to the point where the marginal revenue generated by an additional parking space equals marginal cost. For a fixed number of parking spaces, the height of the parking garage is chosen to minimize garage construction costs.

To further simplify, we assume that the demand for parking at each location (measured as the flow rate of new parkers) is inelastic at D, so that when the garage operator is choosing the parking fee, he trades off a larger market area with a lower fee against higher profit per customer with a higher fee. Let b denote the distance from garage 0 to the boundary of its market area, so that d – b is the distance of its boundary to the nearest neighboring parking garage. Customers choose to park at that garage with the lowest full price. At the boundary, therefore, the customer's full price is the same whether he parks at garage 0 or the neighboring garage. The full price is the parking fee per unit time, times the parking duration, plus the time costs of walking from the parking garage to the trip destination and back again[7]. At the boundary, garage 0's full price is therefore $S_0T + 2vb/w$, and the neighboring garage's is $ST + 2v(d-b)/w$. Thus,

$$S_0T + 2vb/w = ST + 2v(d - b)/w. \qquad (2)$$

Solving out for b yields

[7] We ignore time costs within the parking garage. Introducing them would complicate the algebra without adding much additional insight. If we were to treat them, a customer's expected time costs within a parking garage – searching for a parking spot, and then walking from theparking spot to the garage entrance and back again – would be increasing in x and (within the relevant range) decreasing in h.

$$b(S_0; S) = w(S - S_0)T/(4v) + d/2. \quad (3)$$

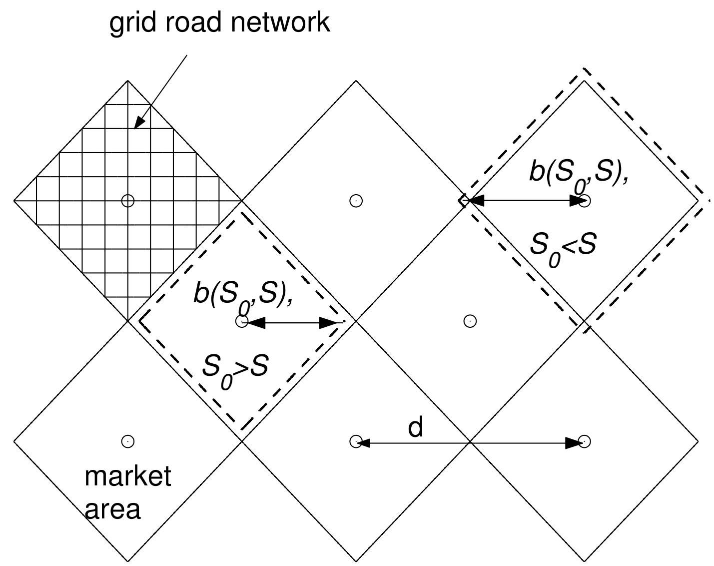

Figure 1: Geometry of Parking Garage Market Areas

Figure 1 displays the geometry of the parking garage market areas. There is a dense grid (or Manhattan) network of roads. Parking garage locations are marked with a circle. The Manhattan distance between neighboring parking garages is d. When all garages charge the same fee, garage market areas are diamond shaped. The dashed line around the parking garage on the center left indicates its market area if it charges a higher fee than its neighbors, while that around the garage on the upper right its market area if it charges a lower fee.

With a grid network, garage 0's market area as a function of b is $2b^2$. Substituting these results into (1) yields

$$\Pi = S_0k - C(k,h;r) \quad \text{s.t.} \quad k = 2DT[w(S - S_0)T/(4v) + d/2]^2. \quad (4)$$

Viewing the constraint as giving $S_0 = S_0(k)$, garage 0's profit function can be written as

$$\Pi = [S + (2v/(wT))(d - (2k/DT)^{1/2})]k - C(k,h;r). \qquad (5)$$

The first-order condition with respect to k is

$$S + (2v/(wT))(d - 3(k/(2DT))^{1/2}) - \partial C/\partial k = 0, \qquad (6)$$

which, as noted earlier, is simply the familiar condition that a profit-maximizing firm will choose that level of output at which marginal revenue equals marginal cost. The expression for marginal revenue requires some explanation. In order to fill an extra parking space, the garage operator must lower his fee by that amount such that his market area includes 1/T more customers per unit time. His market area must increase by 1/(DT) units, which requires that the boundary of his market area increase by 1/(4bDT), which requires in turn (from (3)) that the fee be lowered by $v/(wbDT^2)$. He gains S_0 in revenue from the extra person parked per unit time but loses $v/(wbDT^2)$ in revenue from each of his $2DTb^2$ inframarginal customers. Thus, his marginal revenue is $S_0 - 2bv/(wT)$; from (2), this equals $S + 2v(d - b)/(wT) - 4vb/(wT) = S + 2v(d - 3b)/(wT)$; and substituting $b = (k/(2DT))^{1/2}$ gives (6). His profit-maximizing policy therefore entails charging a customer who parks a duration T a mark up over marginal cost of 2bv/w, which is the walking cost of the marginal customer – the customer at the boundary of the market area. It is perhaps more natural to think of the parking garage operator choosing the parking fee S_0, and adjusting capacity to meet the demand; the same result is obtained.

We now turn to the cost-minimizing design of a parking garage with capacity k. We assume a simple cost function of the following form:

$$C(k,h;r) = rA + (c_0 + c_1h)k + F_0 + F_1h. \quad (7)$$

The fixed cost of constructing a central ramp of h storeys is $F_0 + F_1h$. The average variable cost of a parking space in a garage with h storeys is $c_0 + c_1h$. There is also the cost of the land (the cost function could be simply augmented to include operating costs). Under the assumptions that the ramp takes up land area A_0 and that the floor area taken up by each additional parking space is a:

$$h(A - A_0) = ak, \quad (8)$$

which states that the floor area on each storey of the garage available for parking, times the number of storeys, equals the space taken up by each car times the capacity of the garage. Substituting (8) into (7) gives

$$C(k,h;\, r) = r(A_0 + ak/h) + (c_0 + c_1h)k + F_0 + F_1h, \quad (9)$$

Minimizing (9) with respect to h yields

$$-rak/h^2 + c_1k + F_1 = 0. \quad (10)$$

The cost-minimizing building height is such that the marginal cost of an extra parking space is the same whether the garage is expanded horizontally or vertically. Solving (10) yields

$$h = h(k) = [rak/(c_1k + F_1)]^{1/2}. \quad (11)$$

Differentiating (9) with respect to k gives the marginal cost of a parking space[8]

$$\partial C/\partial k = ra/h(k) + c_0 + c_1h(k). \quad (12)$$

[8] The Envelope Theorem applies. The marginal cost of a parking space equals the marginal cost a parking space, holding h fixed, plus the increase in cost due to varying h. But since h has been chosen to minimize cost, the latter term equals zero.

Finally, combining (6) and (12) gives an equation for the profit-maximizing capacity of the parking garage, from which all the other profit-maximizing variables may be solved for. From total differentiation of this equation, it can be determined how the profit-maximizing capacity of the parking garage, and then the profit-maximizing parking garage height and parking fee, vary with the exogenous parameters. The solution was obtained on the maintained assumption that the parking garage operates at full capacity, with no excess demand. The validity of the assumption is straightforward to establish; if there were excess capacity, the garage operator could raise his profits by reducing the amount of excess capacity; if there were excess demand, the garage operator could raise his profits by increasing his parking fee.

The parking garage operator's problem is, of course, more complicated than this. First, demand per unit area is price-sensitive. Second, in the short run, capacity is fixed but demand varies systematically by time of day, day of the week, and season. If the parking fee is freely adjustable and if the demand per unit area is price sensitive, then the parking garage operator will set the parking fee equal to the maximum of the parking fee that satisfies demand with no excess capacity and the parking fee for which marginal revenue is zero. If the parking fee cannot be varied, then the parking garage operator will set the fee so that average revenue is maximized. Third, there are stochastic variations in demand. Practically, parking fees are not adjusted according to the stochastic realization of demand; responsive pricing is not employed. In the short run, the operator will set the fee so as to maximize expected revenue. Fourth, a parking garage is a durable structure. Thus, capacity is chosen to maximize the present discounted value of profits over the garage's life, rather than profits at a point in time. Fifth, the combination of durability and uncertainty about future demand make the choice of capacity an exercise in irreversible investment à la Dixit-Pindyck . Sixth, not only demand but other aspects of the parking garage operator's economic environment will change over time, including the location and pricing policies of neighboring parking garages.

Two central insights emerge from the above analysis. The first is that "the friction of space confers market power". The discreteness of parking garages, which results from horizontal economies of scale deriving from the fixed cost of constructing a parking ramp, confers market power on parking garage operators. Exercise of this market power in general results in inefficiency, and this inefficiency should be taken into account when formulating parking policy. The second insight is that one manifestation of parking garage operators' market power is strategic interaction between parking garages; above, the parking garage operator's profit-maximizing choices depended on the parking fee set by neighboring parking garages.

3. *Equilibrium and Optimum in the Parking Garage Market*

3.1 Equilibrium

We now solve for the Nash equilibrium of the second-stage price game between parking garage operators[9].

Symmetry implies that $S_0 = S$ in equilibrium. Thus, each market area has area $d^2/2$ and so $k = Dd^2T/2$. Substituting this result into (6) and solving gives:

$$S = \partial C/\partial k + vd/(wT) \quad \text{or} \quad ST = T(\partial C/\partial k) + vd/w. \qquad (13)$$

Thus, for parking a duration T, the parking garage operator charges a mark-up over marginal cost of $vd/w = 2vb/w$, which are the walking costs at the boundary location. From (5), this implies that

$$\Pi = k\,[(vd/(wT)) + \partial C/\partial k] - C(k,h;r).$$

$$= k\,[\partial C/\partial k - C/k + (v/w)(2/(DT^3))^{1/2}k^{1/2}\,] \quad (\text{using } d = (2k/(DT))^{1/2}). \qquad (14)$$

In the first stage of the game, the equilibrium density of garages adjusts such that zero profits are made; k adjusts such that the expression in square brackets in (14) equals zero.

The above specification of the game was chosen for its simplicity. How garages actually interact strategically is an empirical issue that merits detailed attention since it is central to the design of effective parking policy.

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[9] Customers are passive agents in the game, simply choosing to park in the parking garage with the lowest full price.

3.2 Social optimum

We now solve for the social optimum, and compare the social optimum with the spatial competition equilibrium. At the social optimum, k and h minimize the sum of garage costs and walking costs per unit area. The average walking distance for a customer is two-thirds of the distance to the boundary; thus, the average walking costs per customer are 4vb/(3w) = 2vd/(3w) and per unit area-time 2vdD/(3w). The social optimum problem is therefore

$$\min_{h,k} \quad 2C(k,h;r)/d^2 + 2vdD/(3w).$$

Since $d = (2k/(DT))^{1/2}$, this reduces to

$$\min_{h,k} \quad C(k,h;r)DT/k + (2v/(3w))(2D/T)^{1/2}k^{1/2}. \qquad (15)$$

The first-order condition for h is the same in the social optimum as in the spatial competition equilibrium, since both entail cost minimization. The first-order condition with respect to k is:

$$(DT/k)[\partial C/\partial k - C/k + (v/(3w))(2/(DT^3))^{1/2}k^{1/2}] = 0. \qquad (16)$$

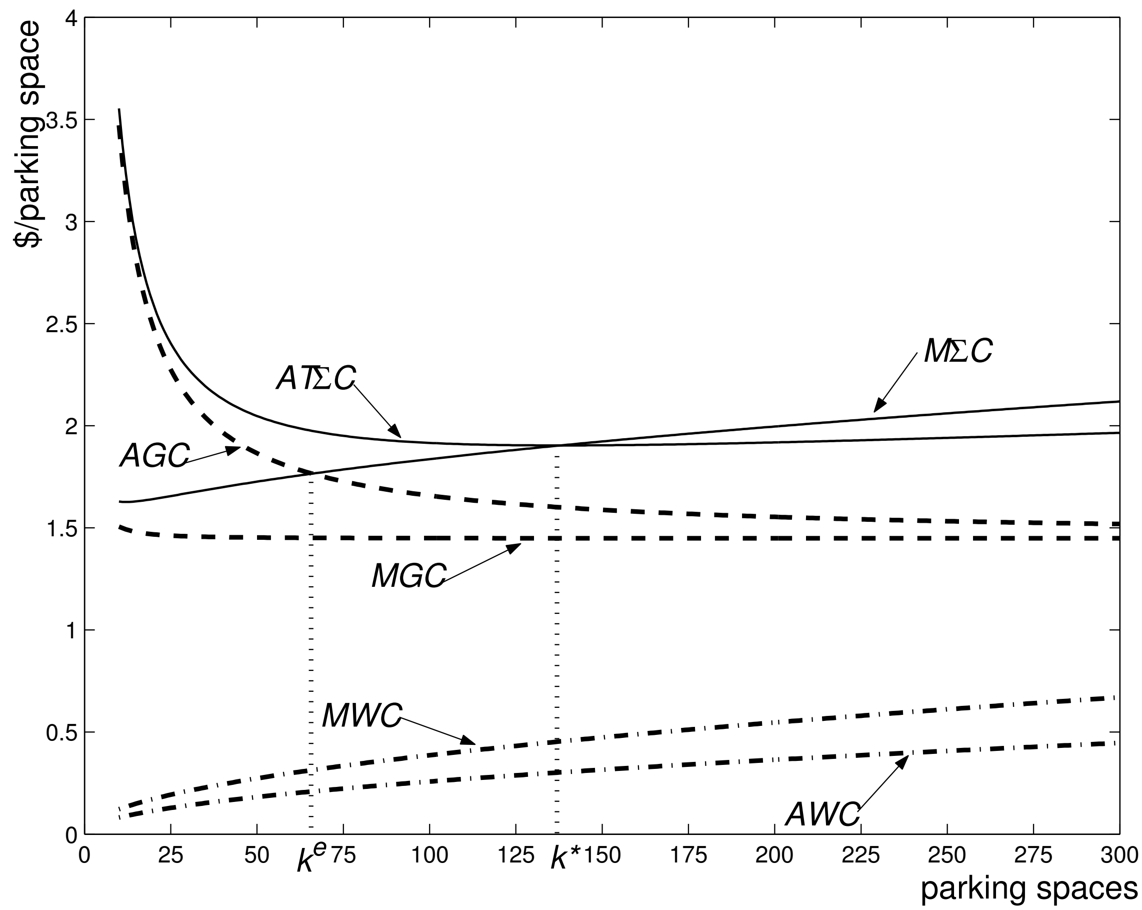

Figure 2: Garage Cost Curves

Note: With time in hours, money in dollars, and distance in miles, the curves are drawn with the following parameter values: D = 7424, T = 2, F_0 = 5, F_1 = 0.625, r = 250,000, $A_0 = 4.52\text{x}10^{-5}$, w = 3, $a = 1.44\text{x}10^{-5}$, v = 20, c_0 = 0.5, c_2 = 0.0625.

Figure 2 displays the relevant average and marginal cost curves with respect to k (taking into account that h varies with k according to (11)). ATGC and MGC are respectively average total and marginal garage construction costs. AWC and MWC are respectively average and marginal walking costs. In the spatial competition equilibrium, the mark-up of the parking fee over marginal garage construction costs is MWC, so that the zero profit condition is ATGC = MGC + MWC. The social optimum occurs at the minimum point of ATGC + AWC. Since an average is minimized where the marginal equals the average, the social optimum occurs where ATGC + AWC = MGC + MWC or ATGC = MGC + (MWC – AWC). Socially optimal values of variables are subsequently denoted by *.

It follows from the geometry of the problem that parking garages and their market areas are inefficiently small in the spatial competition equilibrium. This result is particular to the assumed form of the parking garage game. Also, since efficiency entails pricing garage parking at marginal cost, while the spatial competition equilibrium entails a mark-up over marginal garage construction cost, garage parking is overpriced in the spatial competition equilibrium. This result is, in contrast, quite general since in any reasonable specification of the parking garage game, equilibrium will entail garages exercising some degree of market power and pricing above marginal cost.

3.3 Policies that decentralize the optimum

What would optimal policy entail in this stylized economy with no on-street parking, no traffic congestion and no mass transit? Since aggregate parking demand in the model is inelastic, the overpricing of parking by itself results in no efficiency loss. The efficiency loss stems instead from parking garages that having inefficiently little capacity and inefficiently small market areas. Full efficiency can be achieved by imposing a lump-sum tax of $k^*\tau^*$ on each garage per unit time[10], where τ^* = AWC*, evaluated at the

[10] This is shown in Figure 2. If the garage were to choose capacity k*, it would charge a fee of MGC(k*) + MWC(k*) and receive this amount times k* in revenue. It would incur AGC(K*)k* in garage construction costs and would pay τ^*k^* in taxes. Thus, its

optimum. Full efficiency is not achieved by imposing a tax of τ* per unit time on parking capacity. The parking garage operator would view this tax as equivalent to an increase in marginal construction costs of τ*, and would continue to mark-up the parking fee above this augmented marginal cost by the same amount. In other words, this tax would be fully forward shifted to customers, and would have no effect on the equilibrium level of capacity.

In the model, the optimum can also be achieved through government ownership and operation of parking garages. In reality, government ownership and operation has adverse incentive effects.

Now let us modify the model in three respects, making the derived demand for a trip responsive to the full trip price, introducing traffic congestion, and allowing for employer-provided parking.

3.4 Price-sensitive demand

Analytically, price-sensitive demand is treated by making the quantity of parking demanded per unit area at a particular location a function of the full price of a trip to that location. Walking costs and hence the full price of a trip increase with distance from the parking garage. The price-sensitivity of demand increases the elasticity of aggregate demand faced by the garage operator, which reduces the mark-up of the parking fee over

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profits would be (MGC(k*) + MWC(k*) – AWC(k*) - AGC(k*))k*, which equal zero. Thus, each garage would be pursuing what it views as its profit-maximizing pricing policy, and since profits are zero there would be no incentive for entry or exit.

marginal cost. With price-sensitive demand, the social optimum is solved by maximizing social surplus per unit area rather than minimizing cost per unit area.

Consider now how the price-sensitivity of demand affects the deviation between the spatial competition equilibrium and the social optimum. At a given distance from a parking garage, the quantity of parking demanded is lower in the spatial competition equilibrium than in the social optimum, since the full price is higher. We conjecture that in spatial competition equilibrium, garages continue to have insufficient capacity but that whether they continue to be more densely spaced than in the social optimum depends on the demand elasticity. There are now two sources of efficiency loss in the spatial competition equilibrium, one resulting from inefficient spacing and the other from pricing garage parking above marginal cost.

The price sensitivity of demand affects the policy that decentralizes the social optimum. Since spatial competition equilibrium now entails distortion on two margins, two policy instruments are needed to decentralize the social optimum. First, garage parking should be subsidized such that parkers face marginal social cost, and second, a lump-sum tax should be imposed on each parking garage such that free entry and exit results in efficient spacing.

3.5 Traffic congestion

We assume that the only form of congestion is flow congestion on city streets, and so ignore the congestion caused by cars entering and exiting from parking garages. Consider first the situation where demand per unit area is completely inelastic. Suppose that parking is uniformly distributed over space. Where λ is average trip distance, the flow on roads must be $D\lambda$ per unit area, and travel speed must be consistent with this flow level[11]. Since by assumption demand is insensitive to trip price, the equilibrium is the same whether or not congestion tolls are charged. Suppose instead that parking garages are discretely spaced. Traffic flow is no longer uniform. Since traffic congestion is a convex function of the level of flow, this non-uniformity of flow will lower average travel speed and increase average trip price. Thus, even with inelastic demand and no on-street parking, the spacing of parking garages will affect traffic congestion. The further apart are parking garages, the less uniform is travel flow, and the higher is average congestion. In their choices of locations, parking garages ignore this effect. By itself, this causes parking garages to choose super-optimal spacing, which counteracts the tendency of parking garages under spatial competition to choose sub-optimal spacing. With price-sensitive demand, another, familiar effect arises. If congestion is underpriced, it may be efficiency improving that garages in spatial competition equilibrium set the garage fee above marginal construction cost.

3.6 Employer-provided parking

In the United States, the vast majority of workers use the car on the journey to work, and the bulk of these auto commuters receive free employer-provided, off-street parking. In the downtown areas of the major cities, employees typically receive subsidized rather

[11] As is well known, there are generally two speeds consistent with a flow level. We simply assume that travel is at the higher speed associated with a given flow level, i.e. that traffic flow is congested rather than hypercongested.

than free employer-provided, off-street parking. Employer-provided parking is practically important, but alters only the details of the analysis. Employers decide in which parking garage their employees will receive free or subsidized parking. Some employers are large enough to have some bargaining power, which will soften the garage operators' exercise of market power. When demand is price sensitive, the provision of free or subsidized parking by employers will lower their employees' trip price, leading to more trips, more parking capacity, and more road congestion.

4. Adding On-street Parking

We did not dwell on parking policy in the previous sections since the model omitted two features of downtown parking that are essential in almost all cities, on-street parking and mass transit. This section considers the complications that are raised by on-street parking.

In the downtown areas of almost all major cities, on-street parking is used to capacity throughout the day, and in many of them the on-street parking capacity utilization rate exceeds 100% due to double parking, illegal curbside parking, and parking on the sidewalk. We say that on-street parking under these conditions is *saturated.* Furthermore, in the downtown area of almost all major cities, the on-street parking fee is set inefficiently low (in Boston, the rate is $1.00 per hour), with the result that on-street parking spaces are rationed not only through the fee but also through *cruising for* *parking*. Shoup (2005) reports the results of thirteen studies of cruising for parking; across studies, the average share of traffic cruising for parking was 30% and the average cruising time was 8 minutes. Since the study locations were not random, the results are not representative. Nevertheless, they do indicate that cruising for parking can be important.

For consistency with the model of the previous section, it is assumed that *garage parking* duration is independent of the destination, T. This implies that the *visit* duration at x is L(x) = T - 2x/w, garage parking duration minus the walking time from the garage to location x and back again. Now consider a driver whose destination is a distance x from the nearest parking garage. He chooses on-street parking if its full price is lower than that of off-street parking, and *vice versa.* His full price for garage parking is

$$F_g(x) = ST + 2vx/w. \tag{17}$$

If he parks on street, he chooses a parking search strategy that minimizes the full price of on-street parking. If flow congestion and cruising for parking time are uniform over space, a driver's optimal search strategy is to travel to his destination block, and circle the block until he obtains a parking space. To simplify, we assume that drivers follow this on-street parking search strategy.[12] Then the full price for on-street parking is

$$F_n(x) = fL(x) + vZ(x), \tag{18}$$

where f is the on-street parking fee per unit time, which is assumed to be independent of location, and Z(x) is cruising-for-parking time at location x.

[12] In the previous section, we pointed out that congestion is likely to be heavier in the vicinity of parking garages. Taking this into account would considerably complicate the driver's strategy in cruising for parking.

With identical individuals, which we have assumed[13], cruising for parking time adjusts such that the full prices of on- and off-street parking are equalized. Thus,

$$Z(x) = (1/v)[ST + 2vx/w - fL(x)]. \tag{19}$$

Then

$$dZ(x)/df = (1/v)(TdS/df - L(x)),$$

which indicates that how an increase in the on-street parking fee affects the equilibrium amount of cruising for parking depends on how garage operators adjust the garage fee in response. To simplify, we continue with the assumption that the demand for parking per unit area is inelastic. We assume that garage operators recognize that on-street parking is saturated, and so infer for this that the quantity of garage parking spaces demanded per unit area by drivers with destinations a distance x away from the garage is inelastic at (D - P/L(x))T, where P is the number of on-street parking spaces per unit area. If they reason in this way, as seems reasonable, they perceive that their optimal strategy is independent of the on-street parking fee (as long as parking remains saturated). Then the spatial competition equilibrium garage fee is determined independently of the on-street parking fee, and so too therefore is the full price of garage parking.

Since cruising for parking adjusts to equalize the full prices of on-street and garage parking, the increase in the on-street parking fee has no effect on the full price of on-street parking either. It simply causes cruising-for-parking time costs to fall by one dollar for every extra dollar of revenue raised through the increase in the on-street parking fee.

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[13] Arnott and Rowse (2005) consider the complications that arise when drivers differ in their visit durations and value of time.

Reducing the amount of cruising for parking also reduces the level of traffic congestion, which lowers all drivers' trip costs, not only those who park on street. Thus, *raising the on-street parking fee benefits everyone, even if the additional parking fee revenue is completely squandered.* That is the worst-case scenario. Another, more beneficial scenario is that the local government responds to each dollar increase in on-street parking revenue by lowering the amount of revenue raised from other tax sources by a dollar. Since revenue raised from these other taxes is distortionary at the margin, raising an extra dollar of revenue from on-street parking fees generates a direct benefit of one dollar (the reduction is cruising-for-parking time costs) plus two indirect benefits – the reduction in deadweight loss from raising one less dollar in revenue through distortionary taxation, and the travel time savings from the reduction in congestion deriving from the reduction in cruising for parking. Thus, there is a triple dividend. This seems almost too good to be true, but the logic is sound.

Why then do local governments almost everywhere persist in underpricing on-street parking – setting the parking fee below the level that would eliminate cruising for parking? The answer lies presumably in considerations related to political economy. Downtown merchants are a powerful lobby group. Merchants worry that raising on-street parking fees would drive downtown shoppers to suburban shopping centers, not realizing that the reduction in downtown traffic congestion from doing so would more than offset this effect. Contrary to the apparent belief of downtown merchants, there is good evidence that raising on-street parking rates is almost unambiguously beneficial[14], reducing traffic congestion and cruising for parking times, and stimulating downtown shopping. [15]

While the above model is specific and no doubt simplifies reality, it does provide a neat way of thinking about the relationship between on- and off-street parking. The full price of *parking* is an outcome of the game between parking garage operators, and the level of cruising for parking adjusts to bring the full price of on-street parking up to this level. The full price of a downtown trip is the sum of the full price of parking and the time cost of congested travel (excluding the time costs cruising for parking). Let us consider the effects of a couple of parking policies from this perspective.

The model permits consideration of two elements of on-street policy, the on-street parking fee (or meter rate), and the proportion of curbside to allocate to on-street parking[16]. We have already considered the effect of marginally increasing the on-street

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[14] It would be an exaggeration to claim that raising on-street parking rates benefits everyone. Since doing so increases the *money* costs of travel, while reducing travel time, it hurts those with a low value of time. But those with really low values of time do not drive.

[15] Shoup (2005) argues persuasively for the benefits of "cashing out" free or at least underpriced curbside parking, and documents the beneficial experience of Pasadena, California when it cashed out free parking.

[16] The model is too simple to address some other elements of on-street parking policy. The most obvious is time limits. Time limits make no sense in a model in which everyone who parks on street parks for the same length of time, as assumed in the model. (If the time limits are binding, then everyone parks off street; if they are not, they have no effect.) Time limits are analyzed in Arnott and Rowse (2005) in a model where individuals differ in visit length. With cruising for parking and no time limits, those with longer visit lengths park on street and those with shorter visit lengths in parking garages. The level of cruising for parking adjusts such that the *marginal* parker is indifferent

parking fee. What is the optimal on-street parking rate? According to the model, it is *not* the marginal cost of garage parking. Because garage parking is priced above marginal cost, it is optimal to set the on-street parking rate somewhere between the garage parking rate and the marginal cost of garage parking. The tradeoff is between the deadweight loss associated with pricing on-street parking above its social opportunity cost[17] and the deadweight loss associated with cruising for parking.

What is the optimal amount of curbside to allocate to parking when the on-street parking rate is held fixed at a suboptimal level? Even with identical individuals, as has been assumed, the analysis is complex. Allocating more curbside to parking requires less costly garage space, but reduces road capacity, which slows down traffic. This tradeoff is straightforward. The complicating factor is cruising for parking. According to the model, altering the amount of curbside allocated to parking has an ambiguous effect on the full price of garage parking[18], and hence on the full price of parking. For the sake of argument, assume that it has no effect. According to (19), cruising for parking *time* then remains unchanged. Expected cruising for parking time equals the density of cars cruising for parking, C, divided by the rate at which parking spaces are vacated, P/T: Z =

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between on- and off-street parking. Time limits are potentially effective through altering the identity of the marginal parker, since cruising for parking is lower the lower is the marginal parker's visit duration.

[17] With inelastic demand for parking per unit area, it is optimal to set the on-street parking fee equal to the garage fee.

[18] It can be shown, as intuition would suggest, that the equilibrium capacity of parking garages falls. Cost minimization implies that the equilibrium height of parking garages also falls, which lowers the marginal social cost of a garage space. However, because the density of demand for garage parking falls, this is not inconsistent with increased spacing between parking garages, and hence an increase in the mark-up of the garage fee over marginal cost.

CT/P. Thus, holding constant cruising for parking time, the density of cars cruising for parking increases linearly with the amount of curbside allocated to parking: C = ZP/T. Thus, allocating more curbside to parking increases traffic congestion, even though it has no effect on cruising for parking time.

Consider now optimal policy with respect to parking garages when on-street parking is underpriced. It is optimal to give garages a subsidy per unit of capacity such that the (consumer) garage fee is *below* marginal garage costs. This will result in the full price of parking being below its social opportunity cost, associated with which is a deadweight loss when trip demand is elastic. But by reducing the difference between the on-street parking fee and the garage fee, cruising for parking will be reduced. In addition, a lump-sum tax should be imposed on each parking garage to induce second-best efficient spacing.

Optimal parking policy is evidently complex, even without considering the complications introduced by the heterogeneity of parkers, the non-uniformity of the road network, parking for freight deliveries, resident parking, and mass transit.

Consider now free or subsidized off-street, employer-provided parking. We can imagine that there is a distribution of workers who differ in the extent to which their off-street parking is subsidized. Those who receive no subsidy park on street, those who receive free employer-provided parking park in garages, and in between there is a marginal parker who is indifferent between on- and off-street parking. The stock of cars cruising for parking depends on the full price of garage parking faced by this marginal parker. In the variant of the model in which parking demand per unit area is inelastic, the provision of free or subsidized employer-provided parking enhances efficiency since it reduces cruising-for-parking congestion. In the variant in which parking demand per unit area is price-sensitive, this effect is offset by the increase in deadweight loss due to the excessive trip demand generated by the subsidization of garage parking.

5. Adding Mass Transit

In the introduction, we noted that if all parking spaces in downtown Boston were on street, they would occupy approximately 40% of the land area. From the same data source, if all employees in the area were allocated a parking space, the ratio of the parking area to the land area would be over 225%. If everyone were to commute by car and park in a garage, seven-storey parking garages would occupy over 33% of the land area. In conditions of such high density, the bulk of individuals must take mass transit on the journey to work.

We have identified five important distortions that parking policy must deal with: the market power of garage operators, the underpricing of urban auto congestion, the underpricing of curbside parking, free or underpriced employer-provided parking, and distortionary taxation required to finance the subsidy needed by the transportation authority. We now introduce mass transit. While not a distortion in itself, mass transit considerably complicates the design of parking policy.

There are three principal forms of mass transit, bus, subway, and light rail. Light rail and subways have fixed routes and stations, while bus routing and stops are flexible. The subway has no congestion interaction with cars, buses have considerable congestion interaction with cars, and light rail is in between. In all three forms of mass transit, schedule frequency is variable. Taking as given routing, stops, and service frequency, the within-mode degree of congestion is determined by the rolling stock. Practical policy analysis should, of course, treat the three forms of mass transit separately. Here, to focus on economic principles, it is assumed that the only form of mass transit available is the subway. To further simplify, it is assumed that all trips cover the same distance within the downtown area. Then the mass transit policy variables are the fare, schedule frequency, and rolling stock (thus, the treatment of mass transit is similar to that Kraus and Yoshida (2002)).

Assume that mass transit and auto travel are perfect substitutes, and continue to assume that all individuals are identical. Then in equilibrium the full price of travel is the same whether an individual travels by mass transit, drives and parks on street, or drives and parks off street. Thus, the transport authority's problem is to choose mass transit and parking policy variables so as to maximize welfare or consumer surplus[19], subject to the equilibrium condition that the full price of travel by all three compound modes be the same.

[19] In the case of inelastic demand, the problem reduces to that of minimizing the resource costs of travel, including time costs, subject to the same condition.

An important complication is that mass transit is characterized by decreasing long-run average costs, due to economies of scale in service frequency and route density[20] (Mohring (1972)).

Let us start with the situation where on- and off-street parking are efficiently priced, at the social opportunity cost of a garage space, and where traffic congestion is efficiently priced too. In this first-best setting, it is efficient to set the mass transit fare equal to marginal social cost (which includes the marginal congestion cost imposed by a passenger), and to choose service frequency, service density, and rolling stock such that the direct marginal social cost equals direct marginal social benefit. Because of the increasing returns to scale associated with mass transit operation, pricing mass transit at marginal cost results in operation at a loss. If account is taken of the deadweight loss associated with the tax revenue necessary to fund this deficit, and/or if the transit authority operates under a binding maximum deficit constraint, the pricing and investment rules are modified in familiar ways (Boiteux (1956)).

For the moment, let us ignore employer-subsidized garage parking and the distortion associated with the transit authority deficit, but incorporate the underpricing of on-street parking and road congestion, as well as the market power exercised by parking garages.

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[20] Doubling the number of passengers, rolling stock, and service frequency, holding fixed route density, reduces the social costs of an individual's travel. The degree of congestion remains the same, as does in-vehicle travel time and walking time, but expected waiting/schedule delay time falls. Doubling the number of passengers, rolling stock, and route density, holding fixed service frequency, also reduces the social costs of an individual's travel. The degree of congestion remains the same, as does in-vehicle travel time and waiting/schedule delay time, but expected walking time falls.

Under the assumptions made, the full trip price and the resource costs associated with auto travel (indicated by subscript a) can be calculated as a function of the number of auto travelers, N_a: $F_a = F(N_a)$ and $RC_a = RC_a(N_a)$, without reference to the number of mass transit travelers. $F'(N_a) > 0$ is assumed, reflecting increasing road congestion as the number of car travelers increases. Likewise, the full trip price and resources associated with mass transit (indicated by subscript m) are independent of the number of auto travelers: $F_m = F_m(N_m)$ and $RC_m = RC_m(N_m)$. $F'(N_m) < 0$ is assumed, reflecting travel time reductions deriving from mass transit economies of scale. We assume that there is an interior equilibrium, which requires that $F_a(N_a)$ cut $F_m(N_m)$ from below. The separability between full price functions for the two modes, and between the resource cost functions for the two modes considerably simplifies the analysis. One implication of the separability is that, for each volume of mass transit passengers, the mass transit authority should choose schedule frequency, network density, and rolling stock so as to minimize the resources costs associated with only mass transit travel.

Figure 3 plots these functions on the assumption that overall travel demand is inelastic at $\underline{N}$, so that $N_a + N_m = \underline{N}$. We assume that there is an interior equilibrium, which requires that $F_a(N_a)$ cut $F_m(N_m)$ from below. The equilibrium modal split then occurs where the full prices of auto travel and mass transit are equalized, and total resource costs are the sum of auto and mass transit resource costs, associated with this equilibrium. The mass transit fare should be set at that level such that the equilibrium modal split implied by the equal trip-price condition minimizes total resource costs, or at the lowest non-negative fare that satisfies the deficit constraint on the transit authority, if there is one.

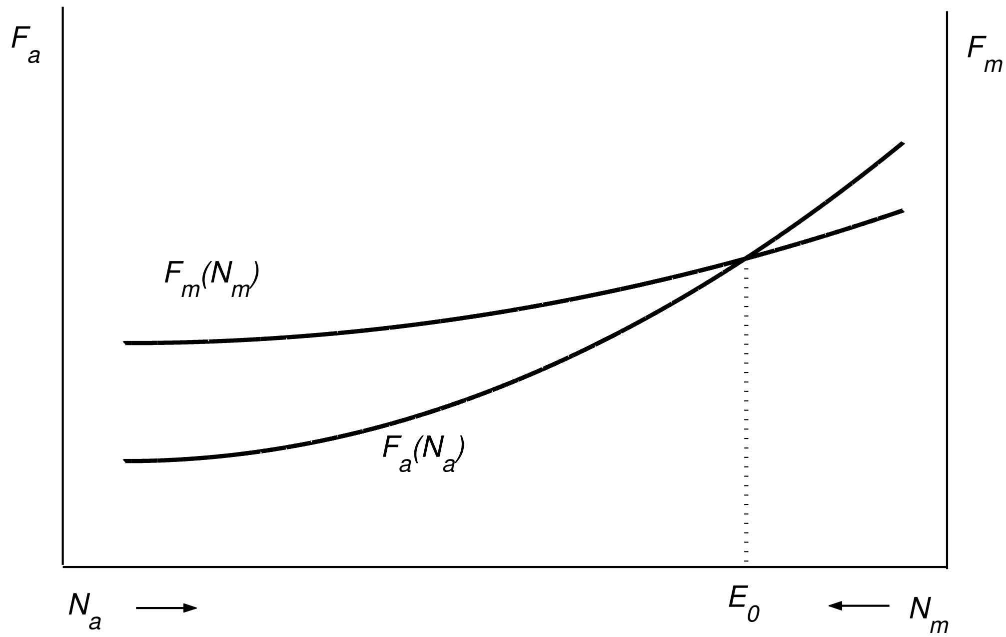

Figure 3: Equilibrium between Auto and Mass Transit

We can now analyze the effects of minimum and maximum parking requirements. Most cities have *minimum* parking requirements, requiring employers to provide at least a set number of off-street parking spaces per employee or per square foot of floor space. Some cities, including Boston and San Francisco, impose *maximum* parking requirements. In terms of the model, which does not consider fluctuations in demand or congestion in parking garages, the only immediate effect of effective minimum parking requirements is to generate vacant spaces in parking garages, wasting resources, which causes the F_a curve to shift up, as shown in Figure 4, and the RC_a curve to shift up as well. This policy stimulates mass transit travel since it causes auto travel to be less efficient.

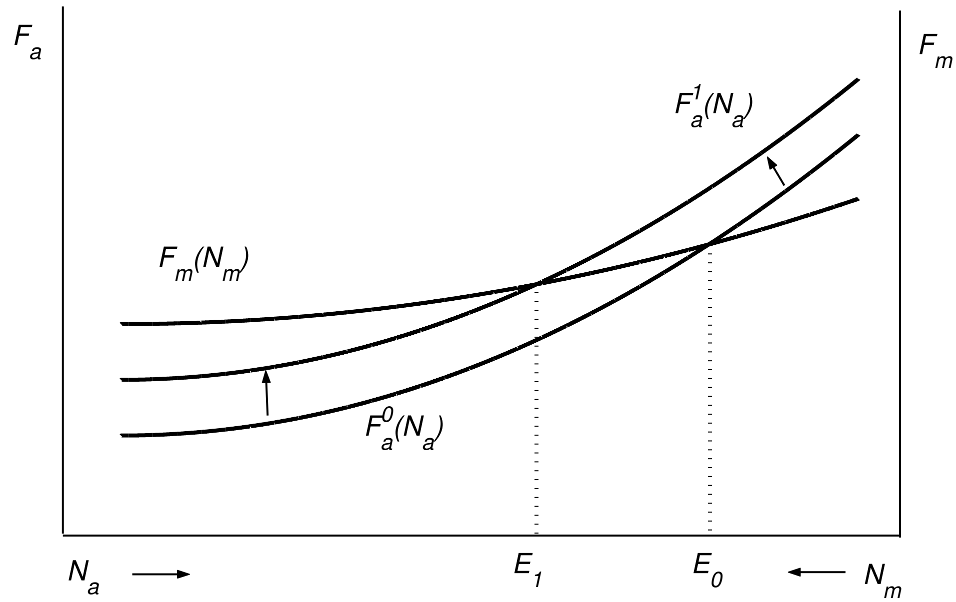

Figure 4: The Effect on Equilibrium of Maximum and Minimum Parking Requirements

The City of Boston has a flexible parking freeze. Its rationale is to restrict the number of auto travelers, in order to exploit economies of scale in mass transit. Having control over the amount of curbside parking and the amount of garage parking gives the government control over the number of auto travelers. Effective maximum parking requirements lower the number of auto travelers to E_1 (Figure 4 applies for both minimum and maximum parking restrictions, though the situations are different). The full price of mass transit travel falls. If the position of the $F_a(N_a)$ curve were to remain unchanged, the full price of car travel would fall even further. What mechanism causes the $F_a(N_a)$ curve to rise in order to re-equilibrate the market is outside the model, and depends on the details of the maximum parking requirements. One possibility is that each garage operator, realizing that the maximum parking requirements prevent neighboring parking garages from increasing their capacity if it increases its fee, will perceive that the restrictions give it more market power, and will accordingly raise the parking fee. Another possibility is that there will be cruising for garage parking, either on street or inside parking garages. The former type of adjustment results in garages earning positive profits in equilibrium, which the maximum parking requirements prevent being dissipated by entry, but not in inefficiency. The latter type of adjustment results in inefficiency. The government should try to expropriate the excess profits earned by parking garages since this raises revenue without distortion. Thus, maximum parking requirements succeed in exploiting economies of scale in mass transit and in reducing the full price of urban travel. Whether they succeed in lowering overall resource costs depends on how garage operators respond to them in their pricing, which is an issue for future research.

In the model of the previous section, with inelastic trip demand, subsidized or free employer-provided parking was beneficial, in reducing the amount of cruising for parking associated with the underpricing of on-street parking. Here there is a contrary effect. In the absence of maximum parking restrictions, such employer-provided parking increases the auto modal share, undermining the transport authority's ability to exploit mass transit's economies of scale.

The above analysis was conduced on the assumptions that travel by car and by mass transit are perfect substitutes, congestion interaction between the two modes does not occur, overall travel demand is completely inelastic, and individuals are identical. Relaxing these assumptions would not only complicate the analysis but might also qualitatively change some policy insights.

The analysis also ignored parking lots. Parking lots are difficult to analyze. The spatial competition between parking lots, and between parking lots and parking garages, is essentially no different from the spatial competition between parking garages analyzed earlier. The difference between the two forms of off-street parking relate to the determinants of capacity. In the absence of restrictions, garage capacity is added until profits of dissipated. But in major urban areas downtown parking lots are an accidental, transitional land use, which typically arise when a developer has demolished a building on a site and is holding the land in parking until it becomes profitable to redevelop the site (Clapp (1977)). As a result, parking lot policy cannot be adequately analyzed without considering issues relating to urban redevelopment, which are beyond the scope of this paper.

6. Conclusion

This paper has examined parking policy from the perspective of a series of increasingly rich models. All were designed to look at "downtown" parking – parking in high-density and highly-congested districts of the city, in which garage parking plays a central role. The first looked at a downtown in which everyone drives to work and parks off street in parking garages. The second added underpriced on-street parking. The third added mass transit.

The models generated a number of policy insights:

--The discreteness of space confers market power on private parking garage operators. Equilibrium in the parking garage market is determined by spatial competition between parking garages. The parking fees set by parking garages are inefficient[21], as most likely is the spacing between them. Parking policy makers should take into account how parking policy affects the corresponding efficiency loss.

--At least in the model presented in the paper, competition between garages determines the full price of parking. The level of cruising for parking adjusts to equilibrate the full price of on- and off-street parking.

--Raising the price of on-street parking (but not beyond the level where on-street parking becomes unsaturated) provides a *triple dividend.* First, cruising for parking is reduced; second, by raising revenue it reduces the amount of revenue that needs to be raised through distortionary taxation; and third, it reduces overall traffic congestion.

--That mass transit is characterized by decreasing average cost significantly affects second-best parking policy. One policy that explicitly attempts to exploit these economies of scale is *maximum* garage parking requirements.

While these insights should prove useful in parking policy analysis, perhaps more importantly the paper has provided a way of thinking economically about downtown parking at a broad level.

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[21] This can be confidently asserted at a high level of generality since the horizontal economies of scale that give rise to the discrete spacing of private parking garages would result in parking garages that price efficiently operating at a loss.

The models in the paper considerably simplify reality (as of course do all models). Future work should consider the complications caused by heterogeneity among travelers (especially with respect to the value of time, parking duration, and distance traveled), the inhomogeneity of space, even in the downtown area, congestion interaction between cars and mass transit, parking by downtown residents and delivery vans, through traffic, and the endogeneity of parking duration. Hopefully, work along these lines will lead to the development of parking simulation models that can reliably forecast the effects of alternative parking policies, leading to more coherent and efficient downtown parking policy.

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