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# Costs and benefits of parking charges in residential areas

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ABSTRACT

We develop a model for empirical evaluation of the social costs and benefits of street parking charges. From the model, we derive an expression for optimal parking charges and occupancy levels: in optimum, parking search costs are balanced against the loss of consumer surplus from unused parking spaces. Contrary to rules-of-thumb common in practice, optimal occupancy levels are not constant but depend on parking turnover rates and parking search costs. We demonstrate the model's applicability in a case study from Stockholm, where parking charges were recently introduced in suburban residential areas. The charges had considerable effects on parking demand, but our analysis shows that the overall welfare effect was a substantial welfare loss. Using parameters and demand functions estimated from the case study, we calculate optimal parking charges and occupancy levels, and show that the welfare loss arises because the introduced charges were considerably higher than the optimal ones.

## Introduction

There has been a surge of interest in the economics of parking pricing and regulation in the last decade. There is still a dearth of empirical studies on parking pricing reforms, however, and in particular studies evaluating social costs and benefits of such reforms. This paper contributes to the literature by developing a theoretical framework for social cost-benefit analysis of street parking charges, and applying it to a case study where street parking charges were recently introduced in suburban residential areas in Stockholm. From the framework, we also derive expressions for optimal parking charges and occupancy levels. The introduced charges turned out to have a considerable effect on street parking demand. However, the analysis shows that the charges generated a substantial welfare loss, since they turn out to be considerably higher than the optimal ones.

Most of the parking literature focuses primarily on city centers, where there is typically excess demand for parking, high opportunity costs of streetspace, and cruising for parking generates external effects especially through increased road congestion. These circumstances have led many transport planners and economists to conclude that street parking charges should be increased, especially in cases where street parking is not priced at all. This paper instead focuses on parking pricing in residential suburbs, where circumstances are different: less excess demand, lower opportunity costs of streetspace, and small external effects from cruising traffic.

We derive expressions for welfare effects, optimal parking charges and optimal occupancy levels in a framework building on the tradeoff between parking search costs (which increase with the occupancy rate) versus the loss of consumer surplus from unused parking spaces. We add to the literature by setting up a model where parking is a two-dimensional good (arrival time and duration),

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and drivers' generalized parking costs consist of search costs plus parking charges, which may depend both on arrival time and duration. The model can be used for empirical evaluation of parking charge reforms, since all variables and parameters are possible to measure. Our expressions for optimal parking charges and occupancy levels are similar to the results of Zakharenko (2016). It follows that optimal occupancy rates are not constant, in contrast to recommendations and rules-of-thumb commonly used in practice. Instead, optimal occupancy rates vary with turnover and search cost rates. The optimal parking charge is non-zero even if search traffic has negligible external costs. This is because parked vehicles generate an external cost for subsequently arriving parkers, increasing their search time for a free parking space. If search traffic generates external costs, the optimal charge increases further, to reflect not only searchers' private costs but the external costs as well.

In the parking literature, the importance of the book by Shoup (2017, 2005) can hardly be overstated, with its emphatic and well underpinned arguments for socially efficient parking regulation and pricing. Since this book was first published, several streams of research have emerged, covering different aspects of parking policy. Inci (2015) provides a review of economic analyses of parking issues, such as garages' spatial monopoly power, employer-subsidized parking, the cost of distortive zoning regulations and several other issues. modeling parking quickly gets complex since it includes many aspects. Theoretical models have therefore focused on different aspects of it. Some of them have analyzed optimal parking prices in a setting where the *demand* for parking, i.e. the number of parking cars in the area, is price sensitive. A seminal paper is Arnott and Inci (2006), modeling the optimal parking charges by trading off the deadweight loss of cruising for parking (with the externality of increased congestion on the street) against the deadweight loss of unused parking spaces. They model cruising for parking as a random-access queue, where the expected cruising time is endogenously determined such that the occupancy is fully saturated. The duration of parking is assumed to be equal for all drivers and fixed. They show that since cruising for parking is entirely a deadweight loss, it is efficient to increase the price of on-street parking to the point where cruising for parking is eliminated. However, it should not be raised beyond the point where parking becomes unsaturated. Several papers have since provided evidence about cruising costs and cruising behavior (Brooke et al., 2018, 2017, 2014; Hampshire and Shoup, 2018; Inci et al., 2017; Lee et al., 2017; Shoup, 2021; van Ommeren et al., 2012).

Other contributions have analyzed how the optimal price of parking impacts the location of parking. For instance, Anderson and de Palma (2004) develop a theoretical framework where drivers want to park in the CBD, but scarcity of parking spaces forces them to park further away. They model how the optimal price of and allocation of on-street parking change with the distance from the CBD (assuming both elastic and inelastic demand). The optimal price internalizes the externality caused by incurring a longer walk from the parking location to the destination (also modelled by Arnott and Rowse (1999)). Anderson and de Palma also show that private pricing of parking spaces in fact yields a socially efficient outcome in this case, as long as cruising for parking does not generate external effects.

Arnott and Rowse (2009) are concerned with the location of parking in terms of private off-street parking versus on-street parking. Assuming inelastic demand. They assume that the desired on-street parking locations are uniformly distributed in space and that private off-street parking is priced such that no cruising for parking is needed to access them. The amount of cruising (causing external cost in terms of congestion) is determined such that it equals the price difference between on-street and off-street parking. In their model the presence of private off-street parking increases the social benefit of optimal pricing of on-street parking, because it reduces the deadweight loss of cruising for parking more efficiently as prices of on-street parking increase. Their model also optimizes the share of streetspace allocated to parking. van Ommeren et al. (2012) confirm empirically that with a lower price gap between curb parking and private parking, cruising time will be much lower.

Zakharenko (2016) and Nourinejad and Roorda (2017) concentrate on an additional dimension, namely parking *duration*. Zakharenko (2016) formulates a model where both the number of parkers and their durations are endogenous, and analyzes optimal parking charges. He also shows that the optimal price for parking is proportional to the rate of arrival of new parkers, and inversely related to the square of the vacancy rate. An important conclusion is that the optimal occupancy level is not constant, but depends on the ratio between arriving parkers and parked vehicles. Another crucial insight is that parked vehicles create an externality for subsequent parkers, which is the reason why the optimal charge depends on arrival rates, not just occupancy rates. He also shows that in optimum, search times will be negligible. The current paper arrives at similar expressions but with a different derivation (see discussion in section 2). Our main purpose is to formulate a welfare rule for evaluating parking charges which affect both the number of parkers and parking duration, and from this welfare rule we derive expressions for optimal charges and occupancy rates similar to Zakharenko's results. Zakharenko also derives additional results, such as the marginal externality created by parked vehicles.

There are only few studies computing welfare effects of parking charges. van Ommeren and Russo (2014) find that free parking induces a welfare loss of 10% of the resource value of the parking space and that a flat rate rather than a time-varying charge reduces the welfare gain 4% of the resource value. van Ommeren et al. (2021) provide a welfare calculation for Melbourne, based on Zakharenko's (2016) theoretical framework.

In our case study, we find that average overall parking demand declined around 25% when parking charges were introduced, with substantial differences between different areas (from 10 to 50% declines). This can be compared to the existing evidence on the cost sensitivity of parking demand. In an early review paper, Marsden (2006) gives a range of price elasticities of parking demand from $-0.6$ to $-0.1$, with $-0.3$ being the most frequently cited value. Kelly and Clinch (2009) report an average value of $-0.29$ for parking frequency, with variations depending on weekday and time of day. A meta-analysis by Concas and Nayak (2012) reports an average elasticity of $-0.39$ ($-0.86$ for non-US countries). Madsen et al. (2013) point out that if estimates of price sensitivity do not control for variations in occupancy and hence search time, the estimates will tend to be deflated, since higher parking charges lead to lower occupancy and hence shorter search times, ceteris paribus. Taking this into account, they estimate a parking price elasticity of $-0.7$. Lehner and Peer (2019) conduct a meta-analysis of parking price elasticities, distinguishing between elasticities parking occupancy, dwell time and parking volume. The elasticities cited above refer to marginal variations of existing parking charges. Empirical evidence of the effects of introducing parking charges on previously unpriced residential streets seem to be scarce; we are not aware of any previous such studies. Krishnamurthy and Ngo (2020) analyze the effects of San Franscisco parking pricing reforms, showing that they have led to improved traffic flow, decreased emissions and increased transit ridership.

Section 2 presents the theoretical framework and derives expressions for welfare changes and optimal parking charges and occupancy rates. Section 3 presents the Stockholm case study and the effects of the parking charge introduction. Section 4 applies the framework from section 2 to the case study, and calculates costs and benefits of the parking charges as well as optimal parking charges. Section 5 concludes.

## Theory

In this section we develop a formal model that allows us to calculate social benefits of a parking reform based on easily measurable data. The model resembles the model in Zakharenko (2016) in that it centers on the tradeoff between search costs and the loss from unused parking spaces, but the derivation of the optimal parking price is different and (arguably) simpler[1] and we also provide a welfare rule usable for empirical case studies. Throughout, we assume that the supply of parking spaces is fixed.

We will treat parking as a two-dimensional good with an arrival time $t$ and a duration $h$. This innovation greatly simplifies the derivation of the welfare rule, optimal prices and occupancy rates. Let $p(t, h)$ be the price to arrive at $t$ and park for a duration $h$, and let $D(t, h)$ be the number of drivers who park at time $t$ for a duration $h$. Let $s(t)$ be the parking search cost for a driver parking at time $t$. Drivers's generalized cost of parking hence consists of the parking search cost $s(t)$ and the parking price $p(t, h)$. The search cost also incorporates any additional walking distance from where a parking space is found. For now, we will assume that cruising for parking generates no external costs; towards the end of this section, we show how external cruising costs can be incorporated in the framework.[2] Moreover, we disregard any possible second-order effects arising from cars discouraged from parking in the area that might park, and cause external costs, somewhere else.

Changes in the price distribution $p(t, h)$ or search cost distribution $s(t)$ may change the parking demand distribution $D(t, h)$ through changes in the total number of parkers, their arrival times and their parking durations. However, we do not need to specify any functional form or structure regarding these dependencies: as we shall see, the optimal prices and occupancy rates can be derived regardless, and empirical welfare evaluations can be carried out just by information about price, search costs and aggregate demand changes.

Consider a parking charge reform consisting of a small change of the price distribution $dp(t, h)$ and a resulting small change of the search cost distribution $ds(t)$. For each parking option $(t, h)$, the corresponding consumer surplus is $-D(t, h)(dp(t, h) + ds(t))$. The total change in consumer surplus $dCS$ is obtained by integrating over all possible arrival times and durations:

$$dCS = -\int\int D(t,h)(dp(t,h) + ds(t))dtdh \tag{1}$$

In applied studies, it is necessary to assume that prices and search costs are constant over distinct time periods $i$, since these variables cannot be measured in continuous time. (In the subsequent case study, we will only distinguish between two time periods: daytime and nighttime.) Normalize the number of parking spaces to 1. Let $H_i$ be the length of time period $i$, let $ds_i$ and $dp_i$ be the changes in search cost and price in time period $i$, let $A_i = \frac{1}{H_i}\int\int_{t\in i} D(t,h)dtdh$ be the arrival rate of drivers during time period $i$, and let $q_i = \frac{1}{H_i}\int\int_{t+h\in i} D(t,h)dtdh$ be the average occupancy rate in time period $i$. Then the change in consumer surplus (1.) generated by the reform can be rewritten as[3]

$$dCS = -\sum_i (A_i ds_i + q_i dp_i)H_i. \tag{2}$$

Parking search times depend on occupancy rates, and can be measured directly, but such data are costly to acquire. However, search times can be calculated approximately from occupancy rates, assuming that a driver searching for parking can check parking

[1] The main difference between the derivations is that Zakharenko starts from micro-foundations, where a continuum of parkers of different types decide whether to park and for how long. Our derivation instead uses a generalization of conventional aggregate demand functions (the "good" is a two-dimensional continuum, and the "price" consists of both parking charges and search costs) to formulate a consumer surplus measure (which is the main focus of our contribution), and from that derives optimal parking charges. The two approaches lead to the same expression for optimal parking charges. Zakharenko also derives other results, including an expression for the marginal externality caused by parked vehicles.

[2] Zakharenko shows that conditional on the optimal hourly parking fee, the number of cars arriving to park has no impact on the consumer cost (or social cost), and the optimal price for parking entry is therefore zero. However, this requires the assumption that external cost arising from any cruising for parking by arriving vehicles is neglected, which Zakharenko justifies by the fact that when parking prices are optimal, the cruising for parking is small. In our suburban context this assumption is also justified by the negligible external costs of traffic.

[3] It is worth pointing out that the resulting consumer surplus is difficult to illustrate in a diagram, since there are two margins of demand: arrival rates and duration. The same occupancy rate can be achieved either by many vehicles parking for a short duration, or fewer vehicles parking for a longer duration. This matters, since total search costs will be higher in the former case. But this means that it is not possible to draw demand on a single axis; we need two demand axes and one (generalized) cost axis. The fact that parking demand is two-dimensional (arrival rates and duration) is ultimately the reason why optimal prices and occupancy rates are different in areas with different arrival rates (turnover), such as residential areas and city centers, even before external costs of cruising traffic are taken into account.

spaces at a constant rate $r$, and that free parking spaces are independently distributed,[4] so searching for parking spaces is a Poisson process (this approximation is also used by Zakharenko (2016) and van Ommeren et al. (2021)). With these assumptions, the average time to find a free parking space is $\frac{1}{r(1-q)}$ where $q$ is the occupancy rate (remember that we assume that occupancy rates are constant within time periods). Letting $c$ be the monetary disutility of parking search time,[5] the expected parking search cost given occupancy rate $q$ is

$$s(q) = \frac{c}{r(1-q)}. \tag{3}$$

This lets us express a change in search cost as a function of a change in occupancy rate:

$$ds = \frac{ds(q)}{dq}dq = \frac{c}{r(1-q)^2}dq. \tag{4}$$

To calculate the total welfare change of the reform, we also need the change in parking revenues. Total parking revenues is

$$R = \sum_i q_i H_i p_i \tag{5}$$

so the change in parking revenues $dR$ from a change in prices $dp_i$ is

$$dR = \sum_i H_i(q_i dp_i + p_i dq_i). \tag{6}$$

Using (2.), (4.) and (6.), the total welfare change of the reform becomes

$$dW = dR + dCS = \sum_i (q_i dp_i + p_i dq_i)H_i - A_i H_i ds_i - q_i H_i dp_i = \sum_i \left(p_i - \frac{cA}{r(1-q_i)^2}\right) H_i \frac{dq_i}{dq_i} dp_i \tag{7}$$

This shows that a price increase will improve welfare if the decrease in search costs stemming from lower occupancy rates (the second term in the parenthesis) dominates the deadweight loss of unused parking spaces (the first term in the parenthesis), and vice versa. Optimal parking charges hence balance search costs against the consumer surplus created by using existing parking spaces. The optimal parking charge $p_i^*$ is obtained by solving $dW = 0$:

$$p_i^* = \frac{cA_i}{r(1-q_i)^2} \tag{8}$$

This expression is analogous to theorem 1 in Zakharenko (2016), which states that the optimal parking charge is proportional to the arrival rate and inversely proportional to the square of the vacancy rate. Eq. (8) also shows that the parking charge is proportional to the search cost per minute and inversely proportional to the search rate. Both search costs and search rates are location-specific, since they depend on the density of parking spaces and the topology of the neighborhood.

The optimal parking charge is always strictly positive. This is because parked vehicles create a negative externality for subsequent parkers by increasing their search time. The optimal charge internalizes this externality. Of course, for low occupancy rates the externality and thus the optimal charge will be negligible. Given how occupancy rates depend on prices, optimal prices can be obtained by solving eq (8.)

In areas with high arrival rates, such as city centers, the optimal prices will be higher and optimal occupancies lower, ceteris paribus, than in areas with low arrival rates such as residential areas. This is pointed out by e.g. Zakharenko (2016), Martens et al. (2010) and de Vos and van Ommeren (2018), but it is worth stressing again since this is different from the widely used practice of targeting a uniform occupancy level, such as the "Shoup rule of thumb" of 85% (which is used in the Stockholm parking strategy, for example).

When occupancy rates are high, drivers often have to park some way from their actual destination, and this extra walk time can be treated as a part of the search cost. A convenient way to include it is to assume that the walk from the parking space to the actual destination is proportional to the search time; the longer the search has to continue, the further away the eventual parking space will be found. This approach means that the search cost per hour $c$ should include a multiplier reflecting this additional walk time.

If cruising for parking causes external costs, for example through (unpriced) emissions, congestion or noise, this can easily be incorporated in the framework as long as external costs per vehicle hour can be treated as constant. Call the total external costs caused by cruising traffic $z$ per vehicle-hour. From (4), we see that external costs resulting from a change in occupancy (and hence search time) becomes $\frac{z}{r(1-q)^2}dq$, and hence a term $\sum_i \frac{zA_i}{r(1-q_i)^2} H_i \frac{dq_i}{dp_i} dp_i$ should be added to the total welfare in eq. (7). This changes the optimal parking

[4] That parking spaces and parkers' destinations are randomly distributed and independent is a crucial difference between the present context (residential areas) and contexts where most parkers have the same destination (such as city centers). In the latter case, parking spaces tend to be filled starting from the common destination outwards.

[5] Including a multiplier to account for additional walking time from the parking space to the actual destination, see below.

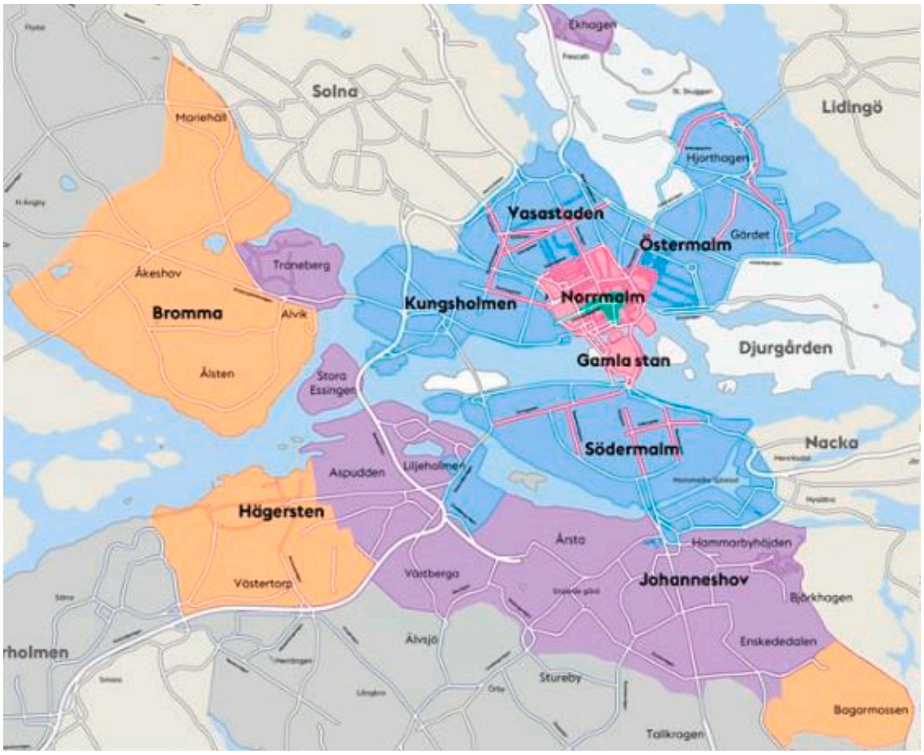


**Fig. 1.** Parking charges in the City of Stockholm decided in 2016. Zone 1 (green) is the inner CBD, zone 2 (red) is the outer CBD and the major through streets in the inner city, zone 3 (blue) the rest of the inner city, zone 4 (purple) is the inner suburbs, and zone 5 (orange) is the outer suburbs. Dark gray zones are zones belonging to the City of Stockholm with free street parking. Light gray areas belong to other municipalities. White zones are parks and forests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

charge in (8) to $p_i^* = \frac{(c+z)A_i}{r(1-q_i)^2}$. In other words, the external cost per search hour should be added to drivers' private search cost. Note, however, that when evaluating welfare effects of a parking policy, changes in drivers' costs are evaluated through a consumer surplus integral (in practice, approximated by the rule of a half as seen below), while external costs are included simply through the difference in external costs before/after the policy.

Next, we turn to empirical applications. In order to evaluate the welfare change of a price change $\Delta p_i$, we need to measure occupancy rates and arrival rates before and after the price change. Moreover, we need to assume that the change in consumer surplus can be approximated by the rule-of-a-half, i.e. that demand functions are approximately locally linear. This assumption is usually necessary for empirical welfare calculations, since the curvature of demand functions can rarely be observed. Note, however, that the changes in arrival rates and occupancy rates can be due to any combination of the total number of parkers, their arrival times, and their parking durations. Finally, if generalized parking costs change simultaneously for several different time periods, it must be assumed that cross-price effects between these time periods are negligible.[6] With this, the total welfare change of the policy $\Delta W$ can be calculated based on easily measurable data: arrival rates (initial rates $A_i$ and their change $\Delta A_i$), occupancy rates (initial rates $q_i$ and their change $\Delta q_i$), the search rate $r$ and finally the search cost per hour $c$.

$$\Delta W \sum_i \left(A_i + \frac{\Delta A_i}{2}\right) H_i \Delta s - \left(p_i + \frac{\Delta p_i}{2}\right) H_i \Delta q_i = \sum_i \frac{c}{r}\left(A_i + \frac{\Delta A_i}{2}\right)\left(\frac{1}{1-q_i} - \frac{1}{1-q_i-\Delta q_i}\right) H_i - \left(p_i + \frac{\Delta p_i}{2}\right) H_i \Delta q_i. \tag{9}$$

[6] This is a standard assumption in applied consumer surplus analysis, although not always innocent. The potential problem is the following. Assume there are two goods, with prices $p_1$ and $p_2$ and demand $D_1$ and $D_2$. Assume that $p_1$ changes to $p_1 + \Delta p_1$, which gives new demands $D_1 + \Delta D_1$ and $D_2 + \Delta D_2$. Then, $p_2$ also changes to $p_2 + \Delta p_2$, giving demands $D_1 + \Delta D_1'$ and $D_2 + \Delta D_2'$. The correct change in consumer surplus, using the rule of half, is then $-\left(D_1 + \frac{\Delta D_1}{2}\right)\Delta p_1 - \left(D_2 + \Delta D_2 + \frac{\Delta D_2' - \Delta D_2}{2}\right)\Delta p_2$. But if the rule of a half is applied to both price changes *simultaneously* (if their demand effects cannot be observed separately), this gives the expression $-\left(D_1 + \frac{\Delta D_1'}{2}\right)\Delta p_1 - \left(D_2 + \frac{\Delta D_2'}{2}\right)\Delta p_2$. The error is $-\frac{\Delta D_1' - \Delta D_1}{2}\Delta p_1 - \frac{\Delta D_2}{2}\Delta p_2$. Often, this error is small compared to the other terms – but not always. In the case study in the present paper, only the daytime price changes (the nighttime price is zero), so the problem does not arise.

**Table 1**
Changes of the street parking charges, decided in 2016 and introduced 2016–2018. Figures have been converted from SEK to € with the exchange rate 10 SEK = 1 €. Daily charging hours for different weekdays are written using the conventional European parking notation: Monday-Friday, (Saturday), *Sunday*. RPP = Residential Parking Permit.

| *Zone* | *Previous charge* | *New charge* |
|---|---|---|
| 1: Inner CBD | 4.1 €/h, all days 0–24. No RPPs. | 5 €/h, all days 0–24. No RPPs. |
| 2: Outer CBD and main through streets | 2.6 €/h 9–17 (9–16), 1.5 €/h all other times. RPP 90 €/month or 6 €/day | 2.6 €/h 7–21 (9–19) *9–19*, 1.5 €/h all other times. RPP 110 €/month or 7.5 €/day. |
| 3: Rest of inner city | 1.5 €/h 9–17. RPP 90 €/month or 6 €/day | 1.5 €/h 7–19, 1 €/h (11–17). RPP 110 €/month or 7.5 €/day. |
| 4: Inner suburbs | No charge | 1 €/h 7–19 (11–17). RPP 50 €/month or 3.5 €/day |
| 5: Outer suburbs | No charge | 0.5 €/h 7–19. RPP 30 €/month or 2 €/day |

## The Stockholm suburban parking charges

### *Parking regulation in Sweden*

The Stockholm metropolitan region has 2.2 million residents. The region is divided into municipalities, of which the City of Stockholm has the largest population by far with nearly one million residents. The City of Stockholm comprises the inner city (350 000 residents) and the surrounding inner suburbs (see map in Fig. 1).

Street parking charges were introduced in Stockholm's inner city in the 1950′s, at first only on a few streets, but subsequently on all inner city streets. Residential parking discounts were introduced in 1981, allowing residents to pay a monthly or daily charge and then park for free on the streets in their neighbourhood. The cost of the discounted monthly residential parking permit has usually been around 50 times the hourly parking charge.

Street parking in Sweden is regulated by two laws. The first one regulates municipal charges for public spaces (*Lag (1957:259) om rätt för kommun att ta ut avgift för vissa upplåtelser av offentlig plats, m.m*), and gives municipalities the right to charge for street parking when it is necessary "to regulate traffic" ("*för att ordna trafiken*"). The law and subsequent court decisions expressly forbids municipalities to charge for street parking for purely fiscal purposes: the purpose must be to curb excess parking demand and ensure that there are parking spaces available for visitors. The priority given to visitor parking over residential parking was further stressed in the Planning and Building Law originating in the 1980′s (*Plan- och bygglagen 2010:900*), which requires real estate developers to ensure that ample parking spaces are provided within the real estate, i.e. not on the street. This means that new residential buildings must supply enough parking spaces for the anticipated parking demand of the residents in the building, whereas street parking should primarily be intended for short-term parking such as visitors and deliveries. This is clearly in conflict with residential street parking discounts.

For these principles to work, however, street parking needs to be regulated, either through pricing or some other regulation. Otherwise there is little incentive for residents to pay (implicitly or explicitly) for parking in the garages or parking lots belonging to the house, since the latter are usually priced. Despite this, there are many residential suburbs where street parking is not priced. Consequently, many residents park on the street, and a considerable share of the legally required off-street residential parking spaces in the building stand empty. Eventually, they are often converted to other uses: parking garages can become storages or workshops, surface parking lots can become gardens.

In theory and according to the planning laws, it is clear what should be done: residential parking should be arranged off-street, and street parking should be reserved for visitors through pricing or time regulations. However, in existing areas it is often (politically and perhaps even ethically) difficult to introduce these regulatory principles retroactively. Residents have chosen locations, travel patterns and car ownership based on existing regulations, and the supply of off-street parking is often highly inelastic, partly because most off-street residential parking spaces are indirectly owned by the residents themselves, through tenant owners' cooperatives.

### *The pricing reform*

This is the background to why the City of Stockholm in 2016 decided to start charging for street parking in residential suburbs, where parking had previously been free. Parking occupancy rates were already considered to be high in some areas, and this problem was expected to grow worse since Stockholm tries to keep up with a fast-growing population by building lots of new residential housing. Moreover, if street parking is not priced, it is difficult to motivate that residential parking should be arranged off-street – in particular since parking spaces constitute a considerable cost in residential building projects. There was hence a clear logic underlying the parking reform. However, the pricing scheme that was introduced was rather crudely designed. All streets in relatively large areas were priced the same, regardless of their initial occupancy rates, and hence several areas became severely overpriced. The target occupancy rate was set to 85%, although the average occupancy rate was already well below that in most areas where parking charges were introduced. Moreover, the target occupancy rate was low considering the low turnover rate in residential suburbs (as pointed out in the theory section).

Despite flaws in the design, the introduction of the charges on previously unpriced residential streets provides a valuable opportunity to study the effects on parking demand. Some of the empirical results of the Stockholm parking reform have been reported in Cats et al. (2016) and Nissan et al. (2020).

**Table 2**
Parking occupancy before and after the introduction of suburban parking charges.

| Area type | Time of day | Zone code | Occupancy before charges | Occupancy after charges | $\frac{\Delta q}{p}$ |
|---|---|---|---|---|---|
| Multifamily housing | Day | 4 | 85% | 62% | −0.0023 |
| Multifamily housing | Night | 4 | 92% | 70% | −0.0022 |
| Multifamily housing | Day | 5 | 84% | 73% | −0.0022 |
| Multifamily housing | Night | 5 | 92% | n/a | n/a |
| Single family housing | Day | 4 | 43% | 23% | −0.0020 |
| Single family housing | Night | 4 | 44% | 22% | −0.0022 |
| Single family housing | Day | 5 | 23% | 21% | −0.0004 |
| Single family housing | Night | 5 | 29% | n/a | n/a |
| Other | Day | 4 | 77% | 50% | −0.0027 |
| Other | Night | 4 | 81% | 52% | −0.0029 |
| Other[1] | Day | 5 | 56% | 60% | 0.0008 |
| Other | Night | 5 | 68% | n/a | n/a |

[1] Areas in zone 5 with dominant land use "other" are excluded in the welfare analysis presented in the following, since the number of parking spaces in those areas is so small and no certain demand effect could be observed.

The changes of the parking charges in all zones are described in Table 1. The focus of this paper, however, is only on the new charges introduced in the suburban areas, zone 4 and 5. The changes in Zone 1–3 had no measurable impact, neither on average occupancy levels nor on the share of parkers using residential parking permits (a time series of inner city parking occupancy is provided in Appendix 1).

Zone 4 consists of the inner suburbs (Traneberg, Aspudden, Årsta, Enskede, Hammarbyhöjden). 62% of the blocks are dominated by multifamily housing, 21% by single-family housing and 17% by other land uses (shops, industries, churches, sports facilities etc.). After the parking charges had been introduced, around 65% of parked vehicles had a residential parking permit.[7]

Zone 5 consists of the outer suburbs (Hägersten, Bagarmossen, most of Bromma). 35% of the blocks are dominated by multifamily housing, 56% by single-family housing and 9% by other land uses. After the parking charges had been introduced, around 60% of parked vehicles in multi-family housing areas had a residential parking permit, while around 50% had it in single-family housing areas.

The total investment cost for the pricing reform was[8] 5.2 M€ (Stockholm Transport Administration, 2019). The main cost components were putting up signs and parking meters in the newly priced areas. According to the city's budgets for 2017–2019, the cost for parking enforcement in the newly priced areas was estimated to be 7.4 MSEK per year, while the corresponding revenues were estimated to be 28.4 MSEK per year.

### *Demand effects of the parking charge introduction*

The new parking charges were introduced in zone 4 during the spring and summer of 2017. Parking occupancy was measured in 150 randomly selected blocks daytime and nighttime before and after the introduction. The sampling of blocks was stratified: 50 blocks of each of three area types (dominated by respectively multi-family housing, single-family housing and other land uses) were sampled, and the samples were then weighted to represent the total land use composition of the zone. Parking occupancy was first measured in April-May 2016, roughly one year before the charges were introduced, and then again in April-May 2018, almost a year after the charges were introduced to allow transient effects to disappear. Parking occupancy was also measured immediately after the introduction, in Sept-Oct 2017. That measurement showed a larger effect on occupancy than the one in April-May 2018, which we interpret as an initial overreaction to the charges. Hence, we use the later measurement to represent the equilibrium effect.

In zone 5, the new parking charges were introduced during February-March 2018. Parking occupancy was measured in 131 randomly selected blocks before and after the charges were introduced, again using stratified sampling. Nighttime occupancy was unfortunately not measured after the introduction of the charges, only before. Parking occupancy was measured daytime and nighttime in Dec 2017-Jan 2018, before the charges were introduced, and then again in October-November 2018, more than half a year after the charges were introduced, which was judged to be long enough after the introduction to allow transient effects to disappear (seasonal variation is negligible).

Table 2 summarizes the average effects of the charges on parking occupancy, by zone, time of day and dominant type of land use. The effects are evident: on average, occupancy levels decreased around 10 percentage points. Note that the reduction in nighttime occupancies are almost as large as the reduction in daytime occupancies, although nighttime parking is still free. This is due to long parking durations; most vehicles park for several days. These long-duration parkers are not only residents in the area, however; a

[7] That this share is so low is perhaps surprising. Remember, however, that there are no parking charges nighttime or weekends, so residents who only occasionally park daytime on workdays won't pay for a monthly residential parking permit. Moreover, studies of where vehicle owners live (according to the vehicle registry) show that a considerable share of parked vehicles belong to non-residents. Some use suburban streets as "park-and-ride" facilities, driving from the outer suburbs and taking the metro to the inner city; some inner city residents park their cars in the suburbs to avoid having to pay the high parking charges in the inner city.

[8] Figures in SEK have been converted to € using the exchange rate 10 SEK = 1€.

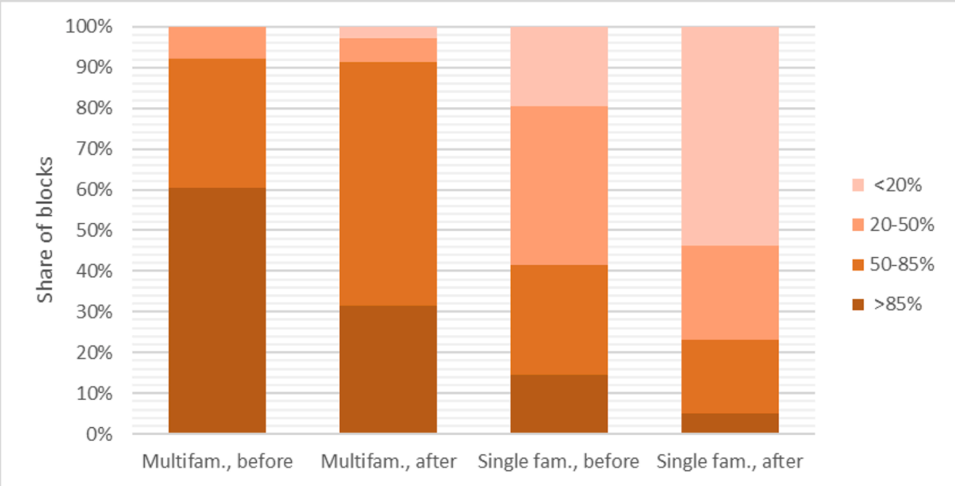


**Fig. 2.** Distribution of occupancy rates before and after the introduction of the parking charges, zone 4.

considerable share are vehicles belonging to residents in the inner city, where parking charges are high and occupancy rates very high.

In the last column, we calculate the ratios between the change in occupancy and the price per hour ($\frac{\Delta q}{p}$). This ratio can be interpreted as a price sensitivity, but it captures not only the effect of the price increase on the demand but also the potential demand rebound effect from lower search costs. The price sensitivities in the last column can easily be compared across areas and time periods. They are similar across most areas and time periods, except for two cases (single-family housing areas and other areas in zone 5) where the charges do not seem to have had any effect on occupancy. We will need the price sensitivities to calculate the optimal parking charges in Section 4.

Since we are interested in the effect on demand for parking, the reported occupancy levels are calculated using the number of available parking spaces before the parking reform. However, the number of available parking spaces was decreased after the implementation of the charges. This reduction of parking spaces thus eliminated some of the search cost benefits achieved initially.

It is unclear why the number of parking spaces was reduced, but it was not an explicit or intentional strategy by the city's transport administration; in fact, it was unknown to the transport administration until the present study was carried out. Most of the reduction seems to have been caused by new parking regulations, prohibiting parking on some streets; some was caused by temporary construction works that were allowed to take parking spaces into account. Such decisions are taken by individual traffic planners at the city's transport administration, each of whom has responsibility for regulations within a certain relatively small area. One hypothesis is that individual traffic planners, consciously or not, noted the new, lower parking occupancy levels, and decided that using street space for other purposes than parking was motivated. In that case, one can hope that there were additional benefits compensating for the loss in terms of longer search times, but we can only speculate.

The average occupancy levels reported in Table 2 hide a large variation in occupancy between streets. Fig. 2 shows the distribution of daytime occupancy levels for zone 4, for multi-family and single-family housing areas. Blocks are divided into four occupancy levels: "over-occupied" (>85% occupancy), "target level" (50–85%), "under-occupied" (20–50%) and "empty" (<20%). It is the over-occupied blocks that constitute the problem that the parking charges were said to be aiming to solve.

Between 2016 (before the charges) and 2018 (after the charges), the share of over-occupied blocks decreased from 61% to 31% in multi-family housing areas, from 15% to 5% in single-family housing areas and from 20% to 8% in other areas. Note that these are the actual occupancy levels, calculated based on the actual, lower number of parking spaces in 2018.

## Welfare analysis

### *Parameters*

To calculate the welfare effects of the suburban parking charges, we need the parameters of the welfare equation (9.) Occupancy rates by type area before and after the reform are presented in Table 2. To evaluate eq. (9.), we also need the parking search rate $r$, the parking search cost per hour $c$ and arrival rates $A_i$.

The search rate $r$ depends on the driving speed while searching, the density of parking spaces in the street, and the extent to which the driver sometimes needs to drive the same street twice, which depends on the network topology. Empirical experiments conducted by the authors suggest that the search rate for the areas studied in this paper is on average 14 parking spaces per minute for cases when several streets must be searched.

As to the search cost per hour $c$, there is relatively little evidence. A meta-analysis by Wardman et al. (2016) estimates this to be 71% higher than ordinary in-vehicle time. That the value is higher is presumably because searching is more onerous and stressful, requiring more effort and attention than normal driving, and that search time is highly unpredictable and hence more akin to delay

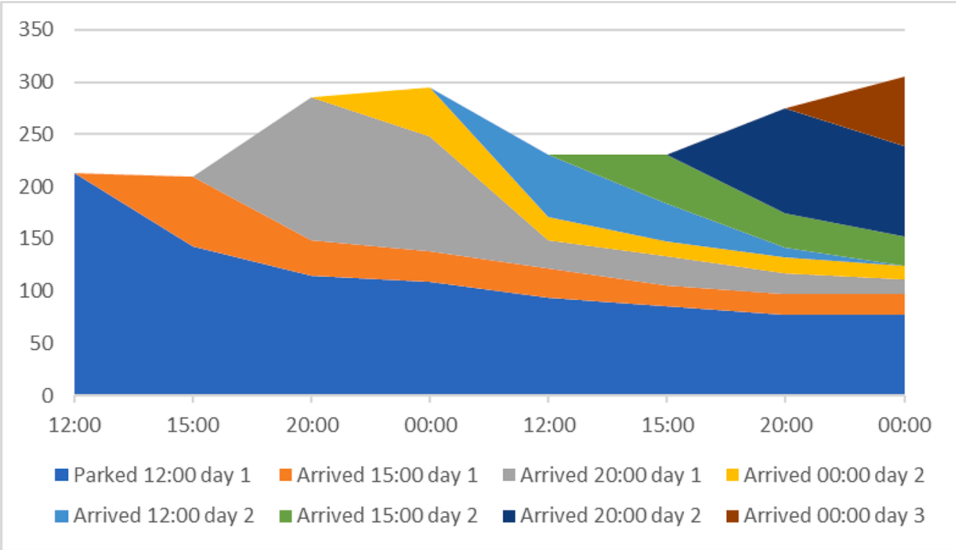


**Fig. 3.** Turnover of parked vehicles, example: Hammarbyhöjden.

**Table 3**
Parameters used for benefit calculations.

| Parameter | Explanation | Value |
|---|---|---|
| $r$ | Average parking space search rate | 14 per minute |
| $c$ | Monetary disutility of searching for parking | 30 €/h |
| $\alpha_d = \frac{A_d}{q_d}$ | Daytime ratio between total arriving parkers during the entire day and the average number of parked cars during the day | 0.44 |
| $\alpha_n = \frac{A_n}{q_n}$ | Nighttime ratio between total arriving parkers (during the entire night) and the average number of parked cars during the night | 0.59 |

time. In addition, additional walking time to the destination from the parking space should be added. Zakharenko (2016) shows that the additional walk time can be substantial, implying that the value of search time can increase by a factor of 6.5 when parking spaces are located along a straight line (since walking is usually slower than driving). De Vos and van Ommeren (2018), on the other hand, find that the walk time externality is relatively small in the residential areas that they study. We assume some walk time externality, and assume a value of search time $c$ is 30 €/hour, which is two to four times higher than the standard valuation of driving time (for which the recommended value in Sweden is 7–12 €/hour, depending on trip purpose and trip length). We assume that search traffic generates no unpriced external costs, since emissions and accidents are approximately internalized by Swedish fuel taxes. If search traffic generates unpriced external costs (such as noise, congestion or negative ambience), these costs should be added as well.

As to arrival rates $A_i$, we only have data for the before situation; arrival rates were not measured after the charges. Hence, we assume that arrival rates are proportional to occupancy rates $A_i = \alpha_i q_i$, where the proportionality parameters $\alpha_i$ are estimated from the before data. The $\alpha_i$ parameters depend on average parking durations, which form a rather complicated pattern. An example is shown in Fig. 3, which illustrates how the composition of parked vehicles changes over time, segmented on their arrival times, based on license plate registrations at 8 different times during 36 h in an area (Hammarbyhöjden).

In the case study, we distinguish between two time periods, namely day ($d$) and night ($n$). The remaining parameters in eq. (9.) are presented in Table 3.

All of these parameters obviously warrant further research. In fact, the literature seems to contain very little evidence on any of these parameters, even though they are clearly important for welfare analysis of parking policies.

### *Welfare effect of the suburban parking charges*

The table below presents effects, costs and benefits of the introduction of parking charges in the suburban zones 4 and 5, by area type, using the welfare formula in eq. (9.). Revenues and benefits are presented as € per parking space; to get total benefits, results must be multiplied by the total number of parking spaces per zone and area type. These totals are in fact uncertain, since there is no comprehensive study of the total number of parking spaces by zone. However, our methodology and conclusions do not depend on the total number of parking spaces, only on average occupancy and the resulting costs and benefits per parking space.

Benefits and revenues are calculated assuming that all parkers pay the full price, i.e. disregarding that some parkers are entitled to the residential discount. If some of the reduction in parking demand is due to fewer residential parkers, this attenuates the net welfare

**Table 4**
Effects, costs and benefits of the suburban parking charges. (*=imputed value based on relative day/nighttime occupancy in other zones).

| | Area 4, multi-family housing areas | Area 4, single family housing areas | Area 4, other land uses | Area 5, multi-family housing areas | Area 5, single family housing areas |
|---|---|---|---|---|---|
| Hourly daytime parking charge (€/h) | 1 | 1 | 1 | 0.5 | 0.5 |
| Daytime occupancy before | 85% | 43% | 23% | 84% | 23% |
| Daytime occupancy after | 62% | 22% | 21% | 73% | 21% |
| Nighttime occupancy before | 92% | 44% | 81% | 92% | 29% |
| Nighttime occupancy after | 70% | 21% | 52% | *81%** | *27%** |
| Revenues (€/p-space/day) | 7.44 | 2.64 | 2.52 | 4.38 | 1.26 |
| Consumer surplus 1: paid charges and reduced demand (€/p-space/day) | −8.82 | −3.90 | −2.64 | −4.71 | −1.32 |
| Daytime search time, before (seconds) | 29 | 8 | 6 | 27 | 6 |
| Daytime search time, after (seconds) | 11 | 5 | 5 | 16 | 5 |
| Consumer surplus 2: daytime search costs (€/p-space/day) | .05 | 0.00 | 0.00 | 0.03 | 0.00 |
| Nighttime search time, before (seconds) | 54 | 8 | 23 | 54 | 6 |
| Nighttime search time, after (seconds) | 14 | 5 | 9 | 23 | 6 |
| Consumer surplus 2: nighttime search costs (€/ p-space/day) | 0.12 | 0.00 | 0.03 | 0.10 | 0.00 |
| **TOTAL NET BENEFITS (€/p-space/day)** | **−1.22** | **−1.26** | **−0.09** | **−0.20** | **−0.06** |
| Number of parking spaces in the area | 10 000 | 3 000 | 2 500 | 5 600 | 3 500 |
| **Total, M€ per year** | **−3.2** | **−1.0** | **−0.1** | **−0.3** | **−0.1** |

effect, since this would mean that the average charge ($\Delta p$ in eq. (9.)) is less than the nominal amount. Qualitative evidence, however – media reports, reactions and comments from the public and so on – indicates that the vast majority of disappearing parkers were not entitled to the residential discount.

The paid charges are a transfer from the parkers to the government, so their net welfare effects cancel out. The remaining loss of consumer surplus, however, stemming from fewer parking spaces being used, is much larger than the benefit of reduced search costs, leading to a total welfare loss for society of almost 5 M€ /year. To this should be added the increased parking enforcement costs of over 7 M€/year, and the investment cost (signs and parking meters) of over 5 M€.

Calculating the welfare change by applying the rule of a half assumes that demand functions are linear. It is quite possible that the demand function is nonlinear, though, in particular when a charge is first introduced (as opposed to when an existing charge is increased). For example, it is possible that the introduction of even a small parking charge would result in a relatively large drop in demand, while subsequent price increases would result in smaller demand effects. Such pattern in the demand has been found for congestion charges (London (Evans, 2008), Singapore (Olszewski and Xie, 2002), and Stockholm and Gothenburg (Börjesson and Kristoffersson, 2017). If this is the case also for parking charges, the rule-of-a-half calculation overestimates the welfare loss of the charge introduction.

In our framework there are no benefits of empty parking spaces. Hypothetically, empty parking street spaces might yield certain benefits. For example, more empty parking spaces might improve traffic flow and give more room for walking and bicycling.[9] On the other hand, parked cars tend to slow traffic down, reducing the severity of accidents. The evaluation framework presented here does not include any such benefits for two reasons. First, we assume that parking regulations are set such that such benefits are balanced versus the benefits of parking spaces. Second, we do not have any data on this, or even indications of such considerations in the city's parking strategy.

Our analysis focuses on pricing of a fixed supply of parking spaces, but parking spaces also have an opportunity cost. In existing streets, parking spaces can be converted for example to greenspaces ("parklets") or bike lanes; when building new areas, street widths and the supply of surface parking are central design parameters. Correct pricing of parking spaces makes comparing the (marginal) value of parking spaces to the value of their alternative use easier, since this reveals the marginal value of parking spaces. Even if it is often difficult to put a definite monetary value on amenities like greenspace, knowing the correct value of the marginal parking space at least makes comparing alternative uses somewhat easier.

As mentioned in the Section 3.2, the total number of parking spaces were reduced in zone 4, sometime after the parking charge introduction. This reduced the search time benefits by almost one half, increasing the total loss of the pricing reform by around 0.3 M€/ year. As concluded in Section 3.2, we can only speculate that the reduction of the number of parking spaces created other kinds of benefits.

*Optimal parking charges*

The results above shows that the parkers' loss of consumer surplus from the unused parking spaces outweighed their reduced search costs. This implies that the introduced parking charges were higher than optimal causing parking spaces to be underused. So, what

[9] Tilahun et.al. (2007) show that parked cars along the cycle lane increase the marginal cost of cycling time by a factor of 1.38, probably because the risk of accidents increases due to poorer visibility or that a car door can be opened.

**Table 5**
Optimal flat daytime hourly parking charge: effects and benefits. (The residential discount is not taken into account when calculating revenues and CS 1; this has no effect on net welfare. See text in previous section.).

| | Area 4, multifamily housing areas | Area 4, single family housing areas | Area 5, multifamily housing areas | Area 5, single family housing areas |
|---|---|---|---|---|
| Optimal hourly daytime parking charge (€/h) | 0.15 | 0.004 | 0.15 | 0.002 |
| Optimal daytime occupancy | 82% | 43% | 81% | 23% |
| Optimal nighttime occupancy | 89% | 44% | 89% | 29% |
| Revenues (€/space) | 1.45 | 0.02 | 1.45 | 0.00 |
| Consumer surplus 1: demand loss and paid charges (€/space) | −1.48 | −0.02 | −1.48 | −0.00 |
| Optimal daytime search time (seconds) | 23 | 8 | 22 | 6 |
| Consumer surplus 2: daytime search costs (€/space) | 0.016 | 0.00 | 0.014 | 0.00 |
| Nighttime search time, after (seconds) | 38 | 8 | 38 | 6 |
| Consumer surplus 2: nighttime search costs (€/space) | 0.069 | 0.00 | 0.069 | 0.00 |
| **TOTAL BENEFITS (€/space)** | **0.05** | **0.0** | **0.05** | **0.0** |
| Number of parking spaces in the area | 10 000 | 3 000 | 5 600 | 3 500 |
| **Total, M€ per year** | **0.14** | **0.0** | **0.08** | **0.0** |

**Table 6**
Sensitivity analysis of optimal charge for zone 4, multi-family housing areas.

| Sensitivity analysis | Parameter change | Optimal daytime charge (€/h) |
|---|---|---|
| Baseline case | | 0.148 |
| Higher search cost *or* Lower search rate | $c' = 2c = 600$ *or* $r' = 0.5r = 7$ | 0.224 |
| Higher price sensitivity daytime | $k_d' = 2k_d = 0.046$ | 0.100 |
| Higher price sensitivity nighttime | $k_n' = 2k_n = 0.044$ | 0.156 |
| Higher turnover rate daytime | $\alpha_d' = 2\alpha_d = 0.88$ | 0.167 |
| Higher turnover rate nighttime | $\alpha_n' = 2\alpha_n = 1.18$ | 0.209 |
| Including MCPF effect (see next section) | Revenues multiplied by 1.3; residential discount reduces gross revenues by 51% | 0.461 |
| Including MCPF effect, no residential discount (next section) | Revenues multiplied by 1.3; no residential discount | 0.711 |

would the optimal parking charges in these areas be? Using eq. (8.) we can calculate the optimal parking charges, using the observed price sensitivities of demand (assuming linear demand functions). We restrict ourselves to only calculating the optimal flat daytime hourly charge, although it is possible – given sufficient data – to calculate an optimal charge that varies by hour over both day and night. However, since we have limited data and since parking durations are so long, calculating the optimal flat daytime rate is a sufficient indication of the optimal charge.

The parameters needed for this numerical simulation can be found in Table 2 and Table 3: Table 4 the ratios between arrivals and occupancy rates $\alpha_d$ and $\alpha_n$, and the demand/price sensitivities $\frac{\Delta q}{p}$, which are taken to be different for day- and nighttime and for each zone and type of area. Given this, optimal flat daytime charges can be calculated from Eq. (8). Results are presented in Table 5.

Optimal hourly charges turn out to be around 0.1 €/hour in multi-family housing areas, and essentially zero in single family housing areas. Optimal occupancy rates are 80–90% in multi-family areas, and obviously stay at their initial level in single-family housing areas. The societal benefits resulting from optimal flat daytime charges would be 0.22 M€/year. These net benefits are much lower than the parking enforcement costs of over 7 M€ per year (plus non-quantified transaction costs for parkers). Enforcement costs are, broadly speaking, a fixed cost, since enforcement is necessary if parking charges are introduced.[10] This means that it is not motivated to introduce parking charges in these areas, since enforcement costs vastly exceed optimal net benefits. (Note, however, that parking charges may still be warranted on particular streets or smaller areas, since occupancy rates vary within the residential areas.)

*Sensitivity analysis*

All the parameters in the model are of course subject to uncertainty. Moreover, they are highly likely to vary between cities and

[10] To some extent, enforcement may have to be stricter the higher charges get, since the temptation not to pay increases. But the cost increase associated with this is relatively small. Stricter enforcement can also to some extent be accomplished by having higher penalties. Enforcement costs vary with the size of the charged area, however, so charging a smaller area reduces enforcement costs.

areas. It is therefore interesting to explore how the optimal charge varies with parameter levels. We use the charging reform for zone 4 as the baseline case in the sensitivity analysis.

Table 6 shows results.

The most important parameters for the benefit calculation are the search cost parameters (the search rate $r$ and the value of search time $c$). The optimal charge depends on the ratio of these two parameters $\frac{c}{r}$; doubling this ratio increases the optimal charge by almost a half. Both search rate $r$ and the value of search time $c$ depend on the specifics of the area – the density of parking spaces, the network topology (if it takes time to reach a new street to search on), and if the street network and the occupancy distribution is such that high occupancy rates generate a lot of additional walking time. Accurate and specific estimates of these parameters are hence important to establish optimal charge levels – but even ballpark estimates will give traffic planners an indication of the right magnitudes.

Turnover rates are also important when search costs are high. Since the occupancy rate is higher during the night, the night turnover rate matters more: doubling it increases the optimal charge by almost 40%. The day turnover rate matters less since search costs are rather low.

Price sensitivities also matter, but less than the other parameters. Doubling the nighttime price sensitivity hardly changes the optimal charge at all; doubling the daytime price sensitivity reduces it by almost a third.

Including marginal cost of public funds (MCPF) benefits, i.e., that revenues can be used to lower distortionary taxes, changes the optimal charge considerably. This additional benefit arises essentially because the price sensitivity for parking is lower than that for working or general consumption. Whether MCPF benefits ("double dividends") should be included in the welfare analysis is discussed in the next section

*"Double dividend" benefits?*

The paid charges are only a transfer from parkers to the city, and hence do not affect the net welfare effect. However, there is a potential efficiency gain if revenues are used to lower distortionary taxes, such as the municipal income tax. Taking such double dividend benefits into account has a major impact on results. The average deadweight loss from taxation – the marginal cost of public funds, MCPF – in Sweden has been estimated to be 30%. This means that there is an additional potential welfare gain of almost 5 M€/year, since gross revenues are around 15 M€/year (taking into account that the residential discount reduces gross revenues by half). This almost exactly offsets the welfare loss from the direct effects of the parking reform. Taking double dividend benefits into account also increase optimal parking charges substantially. For example, the optimal charge in zone 4 multi-family housing areas increases from 0.15 €/hour to 0.46 €/hour, or 0.71 €/hour disregarding the residential discount.

The double dividend benefit arises simply because parking is a less elastic tax base than income or general consumption, and hence parking taxes causes smaller deadweight losses than taxes on income or general consumption. Shoup (2004) and Arnott et al. (2005) argue that this additional benefit may be important. An analogous point is made by several authors in the context of congestion pricing (Eliasson, 2009; Parry and Bento, 2001) and fuel taxes (Lin and Prince, 2009; Parry and Small, 2005). However, even if there seems to be a consensus that such benefits should be accounted for when analyzing Pigouvian taxes, extending the logic to argue for *fiscal* taxes (i.e., taxes *above* the Pigouvian level) on any relatively price-inelastic commodity raises equity and fairness concerns. The "Ramsey tax rule" (Ramsey, 1927) states that it is efficient to raise tax revenues by taxing commodities inversely proportional to the price elasticities of the respective compensated demand. (In the presence of an income tax, optimal commodity taxes also depend on the cross-elasticities with respect to leisure, since leisure cannot be taxed directly (Sandmo, 1987).) However, the Ramsey rule becomes problematic when horizontal equity (that individuals with similar income should pay a similar tax) and vertical equity (that tax payments increase with income) are also of concern. From a horizontal equity point of view, taxing specific commodities (such as parking) for purely fiscal reasons is problematic, because different individuals in the same income group will consume different commodities and hence be taxed differently (Musgrave, 1990). Regarding vertical equity, Atkinson and Stiglitz (1976) point out that while taxes on commodities with low price elasticities tend to have lower deadweight losses, they are also often consumed proportionately more by low-income households. For a thorough review and understanding of their result, we refer to the review by Mankiw et al. (2009), which based on Atkinson and Stiglitz concludes that commodities should be taxed uniformly (unless there are external effects to internalize), given the presence of an optimal linear or non-linear income tax.

Equity concerns are not limited to fiscal taxes but also exist for Pigouvian taxes. However, Mayeres and Proost (1997) shows that optimal Pigouvian taxation has no large negative equity effects as long as other taxes are re-optimized to reach the income distribution target.

There are hence good reasons for not adding double dividend benefits to a welfare analysis of purely fiscal parking charges (i.e., over and above the external costs parking causes), since the equity effects then need to be taken into account as well, along with the efficiency benefit (the double dividend). Moreover, Swedish cities are also expressly forbidden to use street parking charges solely for fiscal purposes (presumably for horizontal and vertical equity reasons): parking charges are only allowed for regulating traffic. For all of these reasons, we do not add any "double dividend" benefit to our welfare analysis, since the charges in this case study are clearly well above the external costs of parking. Had they been motivated as Pigouvian taxes, it would have been reasonable to include a double dividend effect.

The use of revenues is linked to another central issue, however, namely achieving public acceptability for efficient pricing. Similar to congestion pricing, lack of public acceptability is often an obstacle to efficient parking pricing, often using the same type of arguments: "it won't work", "people have to park/drive", "it's unfair". While there is a large literature on congestion pricing acceptability, much less has been written about acceptability of parking charges, although there are exceptions such as Johansson et al.

(2017), Kallbekken et al. (2013) and Ison and Wall (2002).

## Conclusions

Setting optimal street parking charges means balancing low search costs versus allowing existing parking spaces to be used by parkers. This paper develops a framework for empirical evaluation of the social benefits of a parking charge reform where both the number of parkers and parking durations are affected, and applies it to the recently introduced parking charges in Stockholm's residential suburbs.

One of the insights from the framework is that the optimal occupancy rate will be higher in areas with long parking duration (low arrival rates), and hence the optimal parking charge lower, ceteris paribus. This means that optimal occupancy rates will typically be higher in residential suburbs than in city centers or shopping streets. This differs from the common practice to aim for the same, fixed occupancy rate in all areas.

As the case study shows, introducing too high parking charges can cause substantial welfare losses. The introduction of street parking charges in Stockholm's residential suburbs caused a welfare loss of almost 5 M€/year, according to our calculations. In multi-family housing areas, we estimate the optimal flat daytime charge to be around 0.1 SEK/hour, rather than the actual 1 €/hour (zone 4) and 0.5 €/hour (zone 5). In single-family housing areas, the optimal charge is essentially zero, since the initial occupancy rates were already low.

The case study yields some interesting empirical observations. Parking demand is clearly price sensitive, even in areas such as these where parking is dominated by residential parking. The estimated price sensitivity appears to be of the same magnitude across most areas and times of day.

A caveat is that the analysis does not include additional benefits of empty parking spaces, apart from reducing search costs. Such benefits can be positive or negative. For example, more empty parking spaces can make it easier to walk or cycle and reduce accident risks by improving visibility; on the other hand, parked vehicles tend to slow down traffic which can reduce the severity of accidents. Moreover, the analysis deals with pricing a fixed supply of parking spaces, and does not deal with the question of optimal supply. However, pricing parking spaces correctly is a necessary first step. Correct pricing reveals the marginal value of space used for parking, which can then be compared to alternative uses of the street or land, such as greenspace, bike lanes or housing.

Another caveat is that parking charges are sometimes used as a second-best way to price other externalities, notably congestion. Obviously, there are problems with this: parking charges are usually difficult to vary depending on where and when the vehicle drove before it parked, and are usually proportional to the parking duration, which has nothing to do with how large externalities that were created when driving. Nevertheless, if congestion or emissions cannot be priced in any other way, charging parking might be better than not pricing traffic externalities at all. In some special circumstances, parking charges can in fact achieve benefits close to the benefits of optimal congestion charges (Fosgerau and de Palma, 2013).

The Stockholm suburban parking charges were in fact met with less public resistance than had initially been anticipated. One important reason for this was the substantial residential discount, leading to residents getting reduced search costs for a comparatively small charge. It was clear from the public debate that many residents view the street as "theirs", and find it unfair that visitors park on "their" street in order to, for example, take the metro the rest of the way. Such informal park-and-ride uses of residential streets are often frowned upon by residents, although it is in fact often an efficient use of otherwise unused streetspace.

It is common that the price of street parking is too low, leading to long search times, external costs of search traffic and a pressure on planners and politicians to increase street parking supply, although allocating street space to parking tends to have a very high opportunity cost. Most parking studies have studied such situations, for example congested city centers, concluding that it is motivated to increase the price of parking. Indeed, the high occupancy rates in Stockholm's inner city (see Appendix 1) suggest that prices are too low there, especially given the high turnover rates in the inner city during daytime. But it is also possible to put a *too* high price on parking, as shown in the case study presented here. That this risk is real is underlined by the fact that parking revenues are often a convenient source of revenue for a city, since it is at least partially levied on visitors from other constituencies. Just as with any price regulation, it is important to weigh its benefits against its costs. Hopefully, the framework and lessons presented in this paper can help cities do that in a more efficient way.

## CRediT authorship contribution statement

**Jonas Eliasson:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Maria Börjesson:** Formal analysis, Methodology, Writing – review & editing.

## Appendix 1. Parking in the inner city

The parking pricing reform starting in 2016 also increased the price of parking in the inner city, but that did not have any effect on parking demand. The street parking price in the central business district was increased from 41 SEK/h to 50 SEK/h, but the number of parked vehicles was actually 11% higher after the increase. Parking occupancy increased even more, since the number of available parking spaces had decreased after the reform (this was not intentional, and it is not known why this happened).Since the early 2000′s, street parking charges have been increased considerably in real terms, as shown in Fig. 4.

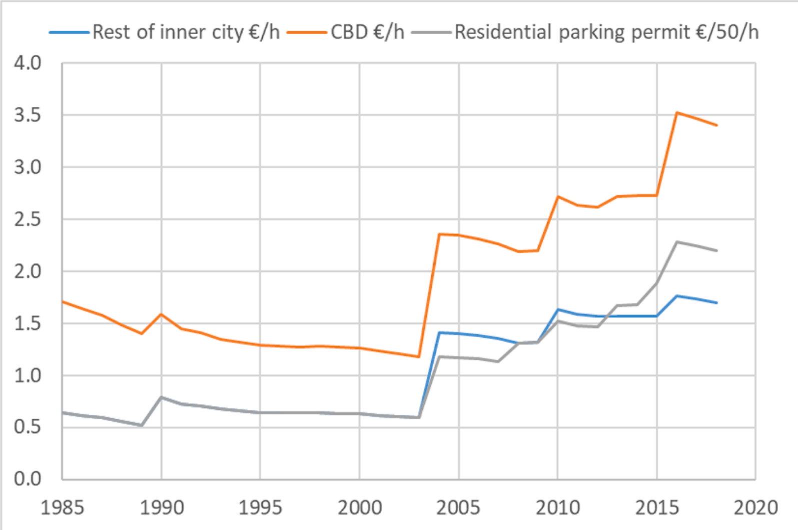


**Fig. 4.** Inner city street parking charges and price of residential parking permit,1985–2018, expressed in 2018 prices and converted by 10 kr = 1 €.

The parking occupancy rate, however has remained virtually constant for more than a decade, as shown in Fig. 5.

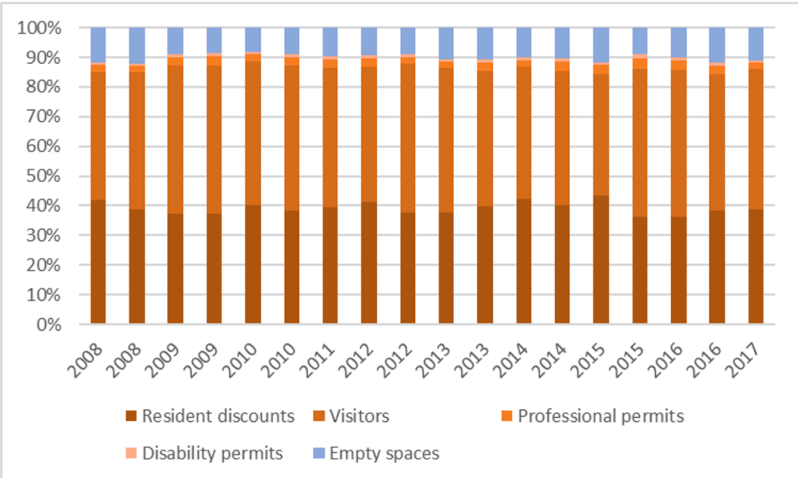


**Fig. 5.** Inner city occupancy rates 2007–2016.

## References


Anderson, S.P., de Palma, A., 2004. The economics of pricing parking. J. Urban Econ. 55, 1–20. https://doi.org/10.1016/j.jue.2003.06.004.

Arnott, R., Inci, E., 2006. An integrated model of downtown parking and traffic congestion. J. Urban Econ. 60, 418–442. https://doi.org/10.1016/j.jue.2006.04.004.

Arnott, R., Rowse, J., 2009. Downtown parking in auto city. Reg. Sci. Urban Econ. 39, 1–14.

Arnott, R., Rowse, J., 1999. Modeling parking. J. Urban Econ. 45, 97–124.

Arnott, R.J., Rave, T., Schöb, R., 2005. Alleviating Urban Traffic Congestion. MIT Press, Cambridge, MA.

Atkinson, A.B., Stiglitz, J.E., 1976. The design of tax structure: direct versus indirect taxation. J. Public Econ. 6, 55–75. https://doi.org/10.1016/0047-2727(76)90041-4.

Börjesson, M., Kristoffersson, I., 2017. The Swedish congestion charges: ten years on - and effects of increasing charging levels. CTS Work. Pap 20172.

Brooke, S., Ison, S., Quddus, M., 2018. Analysing parking search ('Cruising') time using generalised multilevel structural equation modelling. J. Transp. Econ. Policy 52, 202–220.

Brooke, S., Ison, S., Quddus, M., 2017. On-street parking search: a UK local authority perspective. J. Transp. Land Use 10, 13–26. https://doi.org/10.5198/jtlu.2015.600.

Brooke, S., Ison, S., Quddus, M., 2014. On-street parking search: review and future research direction. Transp. Res. Rec. 2469, 65–75. https://doi.org/10.3141/2469-08.

Cats, O., Zhang, C., Nissan, A., 2016. Survey methodology for measuring parking occupancy: impacts of an on-street parking pricing scheme in an urban center. Transp. Policy 47, 55–63. https://doi.org/10.1016/j.tranpol.2015.12.008.

Concas, S., Nayak, N., 2012. A Meta-analysis of Parking Pricing Elasticity.

de Vos, D., van Ommeren, J., 2018. Parking occupancy and external walking costs in residential parking areas. J. Transp. Econ. Policy 52, 221–238.

Eliasson, J., 2009. A cost-benefit analysis of the Stockholm congestion charging system. Transp. Res. A Policy Pract. 43, 468–480. https://doi.org/10.1016/j.tra.2008.11.014.
Evans, R., 2008. Demand elasticities for car trips to central London as revealed by the Central London Congestion Charge. Transp. Lond. Policy Anal. Div.
Fosgerau, M., de Palma, A., 2013. The dynamics of urban traffic congestion and the price of parking. J. Public Econ. 105, 106–115. https://doi.org/10.1016/j.jpubeco.2013.06.008.
Hampshire, R.C., Shoup, D., 2018. What share of traffic is cruising for parking? J. Transp. Econ. Policy 52, 184–201.
Inci, E., 2015. A review of the economics of parking. Econ. Transp., Special Issue on Collective Contributions in the Honor of Richard Arnott 4, 50–63. doi:10.1016/j.ecotra.2014.11.001.
van Inci, E., Ommeren, J., Kobus, M., 2017. The external cruising costs of parking. J. Econ. Geogr. 17, 1301–1323. https://doi.org/10.1093/jeg/lbx004.
Ison, S., Wall, S., 2002. Attitudes to traffic-related issues in urban areas of the UK and the role of workplace parking charges. J. Transp. Geogr. 10, 21–28. https://doi.org/10.1016/S0966-6923(01)00035-7.
Johansson, F., Henriksson, G., Åkerman, J., 2017. Parking benefit districts—the transferability of a measure to reduce car dependency to a European context. Transp. Res. A Transp. Environ. 56, 129–140.
Kallbekken, S., Garcia, J.H., Korneliussen, K., 2013. Determinants of public support for transport taxes. Transp. Res. A Policy Pract. 58, 67–78. https://doi.org/10.1016/j.tra.2013.10.004.
Kelly, J.A., Clinch, J.P., 2009. Temporal variance of revealed preference on-street parking price elasticity. Transp. Policy 16, 193–199. https://doi.org/10.1016/j.tranpol.2009.06.001.
Krishnamurthy, C.K.B., Ngo, N.S., 2020. The effects of smart-parking on transit and traffic: evidence from SFpark. J. Environ. Econ. Manag. 99, 102273 https://doi.org/10.1016/j.jeem.2019.102273.
(Brian) Lee, J, Agdas, D., Baker, D, 2017. Cruising for parking: new empirical evidence and influential factors on cruising time. J. Transp. Land Use 10. https://doi.org/10.5198/jtlu.2017.1142.
Lehner, S., Peer, S., 2019. The price elasticity of parking: a meta-analysis. Transp. Res. A Policy Pract. 121, 177–191. https://doi.org/10.1016/j.tra.2019.01.014.
Lin, C.-Y.C., Prince, L., 2009. The optimal gas tax for California. Energy Policy 37, 5173–5183. https://doi.org/10.1016/j.enpol.2009.07.063.
Madsen, E., Mulalic, I., Pilegaard, N., 2013. A model for estimation of the demand for on-street parking (MPRA Paper No. 52301).
Mankiw, N.G., Weinzierl, M., Yagan, D., 2009. Optimal taxation in theory and practice. J. Econ. Perspect. 23, 147–174. https://doi.org/10.1257/jep.23.4.147.
Marsden, G., 2006. The evidence base for parking policies—a review. Transp. Policy 13, 447–457. https://doi.org/10.1016/j.tranpol.2006.05.009. Parking.
Martens, K., Benenson, I., Levy, N., 2010. The dilemma of on-street parking policy: exploring cruising for parking using an agent-based model, in: Jiang, B., Yao, X. (Eds.), Geospatial Analysis and Modelling of Urban Structure and Dynamics, GeoJournal Library. Springer Netherlands, Dordrecht, pp. 121–138. doi:10.1007/978-90-481-8572-6_7.
Mayeres, I., Proost, S., 1997. Optimal tax and public investment rules for congestion type of externalities. Scand. J. Econ. 99, 261–279. https://doi.org/10.1111/1467-9442.00062.
Musgrave, R.A., 1990. Horizontal equity, once more. Natl. Tax J. 43, 113–122.
Nissan, A., Ntriankos, I., Eliasson, J., Näsman, P., Börjesson, M., 2020. Impacts of on-street parking fees in suburbs. Int. J. Transp. Eng. Technol. 6, 75–85. https://doi.org/10.11648/j.ijtet.20200603.1.
Nourinejad, M., Roorda, M.J., 2017. Impact of hourly parking pricing on travel demand. Transp. Res. A Policy Pract. 98, 28–45. https://doi.org/10.1016/j.tra.2017.01.023.
Olszewski, P., Xie, L., 2002. Traffic demand elasticity with respect to road pricing—some evidence from Singapore. In: Proceedings of the International Conference on Seamless and Sustainable Transport.
Parry, I., Bento, A., 2001. Revenue recycling and the welfare effects of road pricing. Scand. J. Econ. 103, 645–671.
Parry, I.W.H., Small, K.A., 2005. Does Britain or the United States have the right gasoline tax? Am. Econ. Rev. 95, 1276–1289. https://doi.org/10.1257/0002828054825510.
Ramsey, F.P., 1927. A contribution to the theory of taxation. Econ. J. 37, 47–61. https://doi.org/10.2307/2222721.
Sandmo, A., 1987. A reinterpretation of elasticity formulae in optimum tax theory. Economica 54, 89–96. https://doi.org/10.2307/2554346.
Shoup, D., 2021. Pricing curb parking. Transp. Res. A Policy Pract. 154, 399–412. https://doi.org/10.1016/j.tra.2021.04.012.
Shoup, D., 2017. The High Cost of Free Parking : Updated Edition. Routledge. https://doi.org/10.4324/9781351179782.
Shoup, D., 2005. The High Cost of Free Parking. American Planning Association, Chicago.
Shoup, D.C., 2004. The ideal source of local public revenue. Reg. Sci. Urban Econ., Analysis of Urban Land Markets and the Impact of Land Market Regulation 34, 753–784. doi:10.1016/j.regsciurbeco.2003.10.003.
Stockholm Transport Administration, 2019. Plan för gatuparkering 2016-2018. Slutredovisning (No. 2019- 04–25), Trafiknämnden. Trafikkontoret i Stockholms stad.
Tilahun, N.Y., Levinson, D.M., Krizek, K.J., 2007. Trails, lanes, or traffic: valuing bicycle facilities with an adaptive stated preference survey. Transp. Res. A Policy Pract. 41, 287–301. https://doi.org/10.1016/j.tra.2006.09.007.
van Ommeren, J., McIvor, M., Mulalic, I., Inci, E., 2021. A novel methodology to estimate cruising for parking and related external costs. Transp. Res. B Methodol. 145, 247–269. https://doi.org/10.1016/j.trb.2020.12.005.
Van Ommeren, J., Russo, G., 2014. Time-varying parking prices. Econ. Transp. 3, 166–174.
van Ommeren, J.N., Wentink, D., Rietveld, P., 2012. Empirical evidence on cruising for parking. Transp. Res. A Policy Pract. 46, 123–130. https://doi.org/10.1016/j.tra.2011.09.011.
Wardman, M., Chintakayala, V.P.K., de Jong, G., 2016. Values of travel time in Europe: review and meta-analysis. Transp. Res. A Policy Pract. 94, 93–111. https://doi.org/10.1016/j.tra.2016.08.019.
Zakharenko, R., 2016. The time dimension of parking economics. Transp. Res. B Methodol. 91, 211–228. https://doi.org/10.1016/j.trb.2016.04.008.