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Survey methodology for measuring parking occupancy: Impacts of an on-street parking pricing scheme in an urban center

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ABSTRACT

Parking pricing policies can be used as a policy instrument to steer the parking market and reduce the externalities caused by traffic in general and parking in particular. A more efficient management of parking demand can improve the utilization of the limited parking capacity in high-demand areas. Even though parking policies are often a topic of public debate, there is lack of systematic empirical analysis of various parking measures. This paper proposes a survey methodology to empirically measure the impacts of on-street parking policies based on automated parking transaction data. Parking performance is computed based on data available from ticket vending machines calibrated using floating car films. The survey method allows comparing parking occupancy including its temporal variations, allowing the analysis of the accumulated utilization pattern. Average and maximum parking occupancy levels, throughput, parking duration and total fare collection are compared prior and following the introduction of a new parking scheme for visitors to Stockholm inner-city, Sweden. The results indicate that the policy fulfilled its objective to increase the ease of finding a vacant parking place in the central areas and even resulted with underutilized parking spaces.

1. Background and motivation

The rapid growth of motorization in combination with urbanization has led to an increase in traffic demand and consequently increased saturation of the road network. Transport systems are characterized by limited supply due to financial, physical, urban and ecological reasons. It is therefore essential to effectively manage transport demand. One of the major problems associated with increase of traffic is the acute shortage of parking space, especially in urban centers. This shortage arises even though parking facilities consume a substantial share of the urban environment. In Stockholm, Sweden, about 15% of street surface in the city is used for car parking (Stockholmsstad, 2013a).

Pricing policies constitute a set of transport demand management aimed to improve the utilization of a limited capacity. Parking fees can potentially be a useful policy instrument to steer the parking market and reduce the externalities caused by traffic in general and parking in particular. Pricing policies provide a directly accessible and important supply management tool that could be adjusted to adhere to changes in demand levels in order to improve the utilization of the limited parking capacity at high-demand areas. In the case of an underpriced parking, negative impacts include the additional cursing traffic and related accessibility and environmental impacts in addition to its influence on the primary modal choice. Compared with congestion pricing, the introduction of parking policies is simpler, cheaper and politically acceptable and hence common-place (EC, 2007).

Although charging parking fees is a common practice in urban areas, there is no common framework for measuring the impacts of on-street parking pricing. Arguably, this stems from the fact that most studies relied on either manual parking counts or stated preferences surveys. This hinders a systematic and comprehensive analysis of changes in parking utilization and a robust empirical assessment of parking measures. Moreover, even though parking policies are often a topic of public debate and policy making, there is lack of systematic empirical analysis of parking pricing measures.

This paper proposes a methodology to empirically measure the impacts of on-street parking policies. In particular, we propose a survey methodology for measuring parking occupancy including its temporal variations, allowing the analysis of the accumulated utilization pattern. The methodology relies on automatic transaction data from ticket vending machines which is calibrated using observed data collected by a floating car. It allows conducting a comprehensive survey in a cost effective manner and within a

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short time frame. Measures of parking utilization such as average and maximum occupancy levels, throughput, parking duration and total fare collection are compared before and after the introduction of a new parking scheme in Stockholm inner-city in September 2013. The objective of this scheme is to reduce the pre-experiment level of parking occupancy which indicated that parking is underpriced in central areas and to reduce related externalities. The method presented in this paper could be applied in other urban areas that utilize a similar ticketing system.

The remainder of this paper is organized as follows: methods to measure parking occupancy, analyze parking policies and previous findings on the impact of parking pricing measures are reviewed in Section 2. The survey methodology proposed in this study for measuring parking utilization indicators is then presented in Section 3 followed by its application to a case study in Stockholm (Section 4) and the respective short-term results (Section 5). The paper concludes with a discussion on policy implications and suggestions for further studies (Section 6).

2. Literature review on parking pricing

On-street parking limits street capacity since it preempts lanes that otherwise would be used by moving traffic. Furthermore, parking maneuver reduce the capacity and the average speed of the adjacent lanes (Nissan, 2012). On-street parking is often underpriced (Small and Verhoef, 2007). The inefficient management of parking demand results in excessive search time for parking (Arnott and Rowse, 2013) and constitutes a significant contributor to urban congestion (Axhausen and Polak, 1991; Calthrop et al., 2000). Based on previous findings, Shoup (2005) estimated that 30% of the traffic in the city center is attributed to cruising traffic.

Previous studies highlighted the role of regulating on-street parking policies by charging fees or enforcing a maximum parking duration as measures to reduce cruising traffic or as a second-best strategy to effect transport demand (Higgins, 1992; Verhoef et al., 1995; Thomson and Richardson, 1998; Calthrop et al., 2000; Shiftan and Burd-Eden, 2001; Hensher and King, 2001; Petiot, 2004; Albert and Mahalel, 2006; Fosgerau and de Palma, 2013). These studies deployed different approaches to investigate the elasticity to a change in parking fees including the development of analytical economic models and estimating elasticity based on empirical stated or revealed preference survey.

A large range of parking fee elasticity values was reported by previous studies. A TCRP review concluded that parking demand is generally inelastic to price and emphasized that price elasticity could be deceptive without considering the specifics of the price change circumstances (TCRP, 2005). The original pricing level, the possibility to shift parking location and availability of parking substitutes, as well as accessibility by other transport modes will all influence the behavioral response to parking policies (Hensher and King, 2001; Pierce and Shoup, 2013).

Parking pricing policies, their design and impacts have attracted a significant research attention. Parking guidelines suggest that the optimal pricing will obtain a 85% parking occupancy (Shoup, 2005; Litman, 2011). Using a simulation model, Levy et al. (2013) demonstrated how an occupancy rate above 92–93% result with a sharp increase in cruising time which depend on spatial dynamics. However, parking occupancy level may not reflect the overall parking utilization level as the same occupancy might correspond to different parking circulation (e.g. number of cars using a parking place throughout the day).

The trade-off between parking alternative attributes were estimated by previous studies. Axhausen and Polak (1991) found that the walking time from the parking place to the destination is valued more than the in-vehicle access time. This presumably underlies the cruising traffic that circulates within a small radius from the destination. Hilvert et al. (2012) concluded based on stated and revealed preference data that price – both in terms of the overall parking cost as well as the hourly fee-is the dominant factor in parking-related decisions. Van Ommeren et al. (2012) provide empirical evidence for the substitution effect from on-street to off-street parking further away.

Several recent studies analyzed parking pricing policies based on ticket machines data. Kelly and Clinch (2009) analyzed the impact of a 50% price increase in the commercial core of Dublin on the total number of cars parking during different time periods. Their results highlight the importance of considering temporal variations when analyzing parking demand and price elasticity. Similarly, Ottosson et al. (2013) estimated the elasticity based on before–after analysis of ticket machines data in Seattle. The performance-based policy implied an increase, decrease or no change in parking fees based on the discrepancy between measured and desired occupancy levels. Parking elasticity was found to vary by time of day and neighborhood characteristics. They note that average parking duration also changes as a result of price changes. Similarly to these two studies, this paper utilizes data from on-street ticket machines to perform a before-after analysis of a parking pricing policy. An enriched analysis approach calibrates the machine data with floating car data for calculating a series of parking utilization indicators as detailed in the following section.

3. Survey methodology for measuring parking utilization

This section presents a methodology for measuring parking utilization. Three data sources are considered in this study: (a) transactions from on-street ticket vending machines, also known as parking meters; (b) floating car video films, and; (c) on-street parking supply repository. The following explains how these data sources are processed, integrated and used for computing measures of parking utilization.

On-street ticket vending machines provide a direct and automatically collected data on revealed-preference parking choice. This enables a wide spatial coverage concerning parking activities over a long time period without an additional data collection cost. Each transaction on a vending machine is recorded in a parking database management system. A record on machine j contains information on the incoming and outgoing time stamps for transaction $i \in I_j$, $\tau^+_{i,j}$ and $\tau^-_{i,j}$, respectively. I_j denotes the set of transactions of a vending machine situated at street block j.

The load on street block j at time t based on the ticket machine data, $\breve{l}_{j,t}$, is the residual between the sum of all incoming and outgoing flows. Alternatively, it could be calculated as the sum of transactions that started prior to t and finished later than time t:

$$\breve{l}_{j,t} = \sum_{i\in I_j} \delta^+_{i,j}[0,t] - \sum_{i\in I_j} \delta^-_{i,j}[0,t] = \sum_{i\in I_j} \left(\delta^+_{i,j}[0,t] \cdot \delta^-_{i,j}[t,\infty]\right) \tag{1}$$

where $\delta^+_{i,j}[t_1, t_2]$ and $\delta^-_{i,j}[t_1, t_2]$ are dummy variables that indicate whether the incoming or outgoing record, respectively, occurred within the respective time window. This implies that $\delta^+_{i,j}[t_1, t_2]$ equals 1 if $t_1 < \tau^+_{i,j} < t_2$ and 0 otherwise and similarly for $\delta^-_{i,j}[t_1, t_2]$.

The parking load derived from the ticketing machines may not reflect the actual parking load on the corresponding street block. Vending machine data does not contain information on vehicles that are exempted from paying a fee (e.g. street residents, hybrid vehicles), those paying with other means (e.g. SMS) and illegal parking. In addition, it contains the time stamps corresponding to the ticket issuing and the expected departure time which may differ from the actual departure time. Furthermore, drivers may

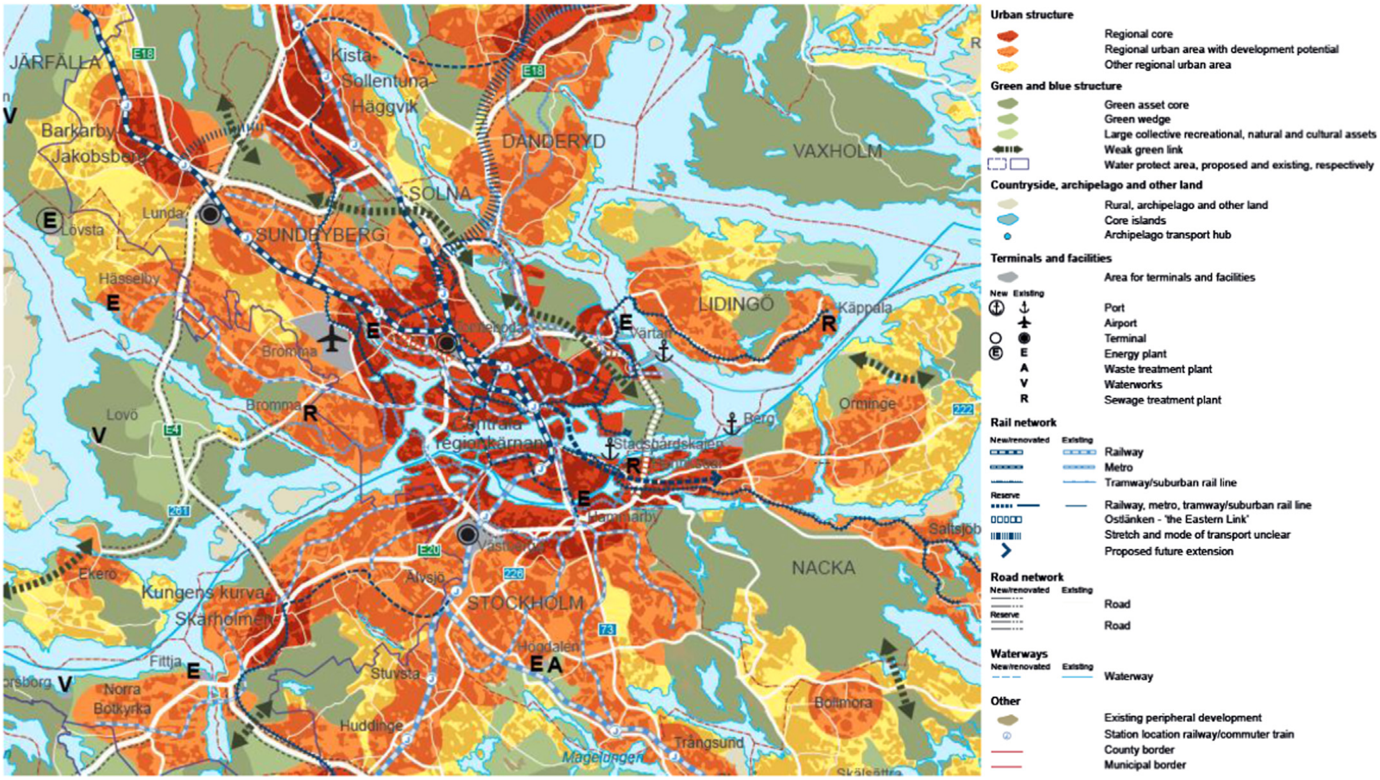

Fig. 1. Stockholm land use map (*Source:* Stockholm Regional Development Plan, 2010).

issue a ticket from a vending machine that is not located directly next to where they parked. Assuming that drivers use the closest vending machine and a good coverage of vending machines, this should not distort the analysis.

Floating car data is used in this study to calibrate data collected by ticketing machines. We start by processing the vending machine data to calculate the momentary parking load on each street segment. The actual number of vehicles parking on each street block is then obtained from video films collected by the floating car on several weekdays. Data from manual parking survey could be used for the same purpose. By comparing the actual load on block j at time t, $l_{j,t}$, and the respective $\underset{\vee}{l}_{j,t}$, *measurement ratios* between machine and ground-truth are established

$$\omega_{j,t}=\frac{l_{j,t}}{\underset{\vee}{l}_{j,t}} \tag{2}$$

$\omega_{j,t}$ is used to correct the parking load obtained from machine data for the respective street block and time-of-day periods. Weights may vary for example because of the composition of the parking population (e.g. share of residents) and the prominence of illegal parking. Moreover, weights are computed separately for the before and after periods in order to control for other changes (e.g. new fare collection method, enforcement).

Parking occupancy is an important measure of parking performance as it reflects the intersection between parking demand and capacity for a given price. The calibrated *occupancy rate* is thus calculated as

$$k_{j,t}(p_{j,t}) = \frac{l_{j,t}}{c_{j,t}} \tag{3}$$

where $c_{j,t}$ and $p_{j,t}$ are the parking supply capacity and price on street block j on the respective time period. Note that number of available parking places could vary over the day depending on the parking regulation. The *maximum occupancy rate* is calculated by taking the max daily value of the occupancy rate.

Performance measurement of parking utilization is not limited to parking occupancy. *Throughput*, also known in the literature as turnover, is a measure of parking circulation and is defined as the average number of vehicles that arrive within a certain time window $[t_1, t_2]$ per number of parking places on a certain street block j

$$v_j[t_1, t_2]=\frac{\sum_{i\in I_j}\left(\delta_{i,j}^{+}[t_1, t_2]\bullet\omega_{j,\tau_{i,j}^{+}}\right)}{c_{j,t_1}} \tag{4}$$

The *average parking duration* at time t is computed based the elapsed time between incoming and outgoing time stamps of cars currently parking at the respective street block

$$\bar{d}_{j,t}=\frac{\sum_{i\in I_j}\left(\delta_{i,j}^{+}[0,t]\bullet\delta_{i,j}^{-}[t,\infty]\bullet\left(\tau_{i,j}^{-}-\tau_{i,j}^{+}\right)\right)}{\underset{\vee}{l}_{j,t}} \tag{5}$$

Finally, the *total fare collection* (TFC) during a certain time window is calculated as

$$z_j[t_1, t_2]=\sum_{i\in I_j}\left(\delta_{i,j}^{+}[t_1, t_2]\bullet p_i(\tau_{i,j}^{+}, \tau_{i,j}^{-})\bullet\omega_{j,\tau_{i,j}^{+}}\right) \tag{6}$$

where p_i is the price associated with parking instance. It might be directly available from the vending machine data or could be assigned based on the pricing policy and as a function of $\tau_{i,j}^{+}$ and $\tau_{i,j}^{-}$.

4. Case study and data collection

The survey and analysis methodology were applied to assess a parking pricing scheme in Stockholm. The following sections provide the case study transport and in particular, parking context, followed by the details of the policy implementation and data collection.

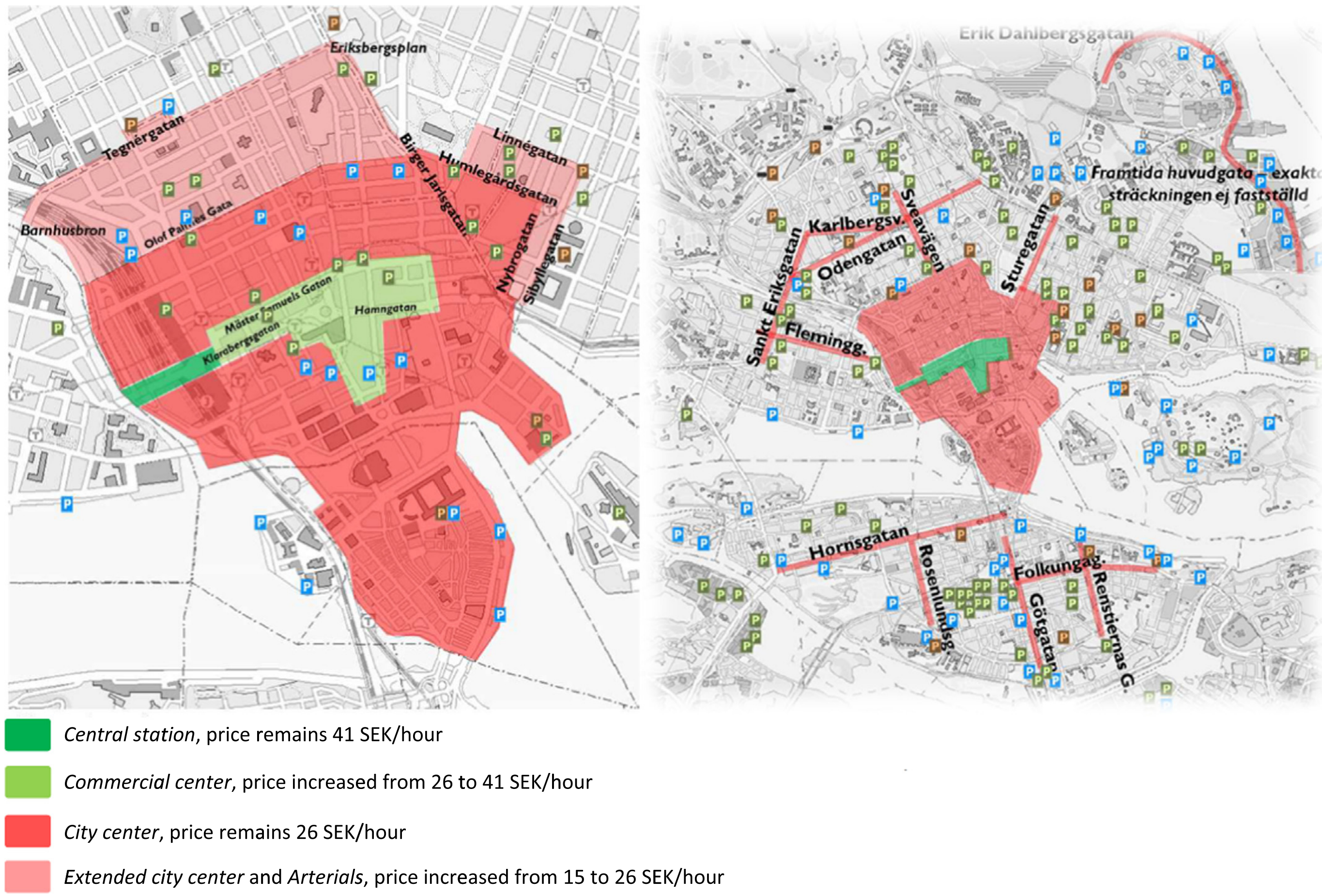

Fig. 2. Parking price changes in the city center (left) and resulting zones in the entire inner-city (right); *Source*: Stockholmsstad (2013a).

4.1. *Case study background*

Stockholm, the capital of Sweden, constitutes the core of the largest and fastest growing metropolitan area of Sweden with 2.16 million inhabitants in 2014. In the late 19th century and early 20th century, the city grew gradually from the old town to encompass neighboring islands. Stockholm is famous for its long-term monocentric planning with a dominant mixed-use central core. The case study area, Stockholm city center, is highly accessible by public transport and is served by an extensive network of commuter train, metro and bus lines (Fig. 1). Public transport ridership data shows that 70% of the inhabitants of the central part of Stockholm County use public transport at least several times a week and 54% of all trips are carried out by public transport, with this percentage increasing to 80% for trips with a destination in the case study area which constitutes the metropolitan core (SL, 2013). Congestion charging was introduced in Stockholm on a permanent basis in August 2007 and encompasses the entire inner-city area. Unlike congestion charges, the City of Stockholm is sovereign to determine parking zones and fares.

It is estimated that approximately 40,000 cars park on-street in Stockholm inner-city on an average working day. Almost 50% of inner-city residents use on-street parking when at home, whereas approximately one third of them use a private parking lot and the rest pay for a parking garage (Stockholmsstad, 2013b). As part of its urban mobility strategy, the City of Stockholm set an objective that “demand for parking spaces should not exceed 85% of those available by 2030” (Stockholmsstad, 2012). A recent survey among Swedish municipalities found that promoting public transport usage and improving the urban space were mentioned in Stockholm among the most prominent arguments for making parking less attractive (Hamilton and Braun Thörn, 2013). Hamilton et al. (2014) analyzed the determinants of congestion pricing acceptability based on a large survey in Helsinki, Lyon and Stockholm. The authors concluded that attitudes towards congestion charges are strongly linked to general attitudes related to environmental concerns, public interventions and various kinds of pricing policies (including user and scarcity pricing). Given the high support in Stockholm for congestion charging and the prevalence of associated attitudes, the political climate in Stockholm supports parking prices increase.

Out of the parking garages in the inner-city, 40% are owned by the municipality which offer approximately 8400 parking spaces across the inner-city. The municipality-owned parking lots and the largest private operator, Q-park, offer together 3800 parking spaces in the city center (Envall, 2009). Residents in each area can apply for purchasing a parking card for 800 SEK per month without a guaranteed parking place. There is no data available on the number of parking spaces available in private properties. An on-going project aims to compile parking supply data on off-street parking and parking garages.

4.2. *Policy implementation*

The City of Stockholm implemented a new parking scheme in Stockholm's inner-city in fall 2013. This scheme is designed to address some of the objectives that the city has defined in its overarching mobility program (Stockholmsstad, 2012). This program states that public transport and non-motorized modes should be prioritized over private cars and that moving traffic should be prioritized over stationary traffic. These objectives concur those identified by Mingardo et al. (2015) as the main objectives in the end of the second phase in the evolution of parking policies in European cities. In line with results from analytical models, the City of Stockholm aims to reach the desirable 85% parking occupancy rate compared with the current level of 90.9% as measured in the 2011 parking survey in the inner-city (Stockholmsstad, 2013b). The manual parking survey is conducted twice per year and is based on counting the number of cars parking in high-demand parking areas around midday. Each road segment is counted once. The high occupancy level indicated that parking was under-priced, hence leading to an inefficient utilization of parking supply and inducing externalities such as increase in cruising traffic and reduced accessibility. The City of Stockholm decided therefore to increase parking fees on high-demand street blocks in the inner-city.

There are three pricing levels for on-street parking in Stockholm which are depicted as *Green*, *Red* and *Blue*, and have an hourly parking fee of 41, 26 and 15 Swedish Crowns (1 USD worth approximately 7 SEK), respectively. These pricing zones cover the entire study area of Stockholm inner-city. A new scheme was implemented in August 2013. The new policy involves the implementation of the following measures (Fig. 2):

(1) Extending the *Green* zone – the *Green* zone which was restricted to the *Central station* and its immediate surrounding was extended to encompass the *Commercial center*, which was previously part of the *Red* zone.
(2) Extending the *Red* zone – the *Red* zone extends from the *City center* to the directly attached *Extended city center* which previously had a *Blue* pricing level.
(3) Introducing the *Red* zone on main *Arterials* in the inner-city which were also *Blue* level beforehand.

The new scheme extends thus geographically the current parking zone borders so that parking fees increase where these zones are extended and remain unchanged on all other streets. The result of the superposition of these three measures is shown on the right part of Fig. 2. In addition, Table 1 classifies the street groups into price change categories and provides the respective number of parking spaces and hourly fee. The continuous *Green* area covers now additional 150 parking spaces in the *Commercial center* in addition to the previous 65 in *Central station.* The former is thus subject to a 15 SEK increase – from 26 to 41 SEK, labeled as *High increase*. The Red zone consists of the area surrounding the *Green* zone – 800 in the *City center* and additional 500 in the *Extended city center*-as well as 1000 parking spaces along the *Arterials*. The 1500 parking spaces that changed from *Blue* to *Red* are thus subject to *Low increase* from 15 to 26 SEK. Finally, the remaining *Residential streets* constitute the *Blue* zone (the unmarked areas in Fig. 2). In addition these street segments that remained in the *Blue* area, the *Central station* and the *City center* areas remained *Green* and *Red*, respectively. These three categories are collectively denoted in this study as *Unchanged* since the hourly parking fees remain unchanged. Unlike the *High increase* and *Low increase* categories, it contains various price levels ranging from 15 to 41 SEK per hour.

Table 1
Parking fee and capacity before and after policy introduction.

Price change category	Description	Number of parking spaces	Parking fee [SEK/hour]		
			Before	After	Diff.
High increase	*Commercial center* (*Red->Green*)	150	26	41	15 (+58%)
Low increase	*Extended city center* (*Blue->Red*)	500	15	26	+11 (+73%)
	Arterials (*Blue->Red*)	1000			
Unchanged	*Central station* (*Green*) *City center* (*Red*) *Residential streets* (*Blue*)	65 800 approx. 30,000	15–41	15–41	0 (0%)

The *Unchanged* category is used in this study for control purposes but has to be treated with caution. In a complex urban context it is not possible to design a perfectly controlled experiment with otherwise identical street blocks simultaneously subject to alternative policy measures. While referring to street categories, the parking demand for individual street blocks is influenced by its micro-environment (e.g. businesses, private parking lot or turning permissions). The *Unchanged* category consists of streets located in direct proximity to the parking taxation zones; perpendicular or parallel to arterials, or; elsewhere within the inner-city. These street blocks share in common that parking prices remained unchanged during the study period. Nevertheless, it is expected that for those located in proximity to price changes parking utilization will increase as their prices became more attractive in relative terms. The comparison of parking utilization on these streets can be used as a benchmark and shed light on the overall changes in parking patterns.

The parking fees on off-street car parks and parking garages positioned in each price change category were reviewed. An average fee of 55.71 SEK per hour is charged in the *High increase* area, while hourly fees in the *Low increase* and *Unchanged* areas are 23.89 and 29.74 SEK, respectively. Off-street prices remained largely unchanged during the study period.

4.3. Data collection

As mentioned in the survey methodology section, three data sources are considered in this study: transactions from ticket vending machine, floating car films and a parking supply database.

4.3.1. Ticket vending machines

Ticket vending machines constitute the primary parking payment method, enabling visitors in Stockholm inner-city to pay for their parking using debit or credit cards. In 2012, when vending machines were almost the sole payment method for visitors, a total of 267 million SEK (Stockholmsstad, 2013a) were collected. The entire study area is subject to parking pricing zones and is covered by multi-space vending machines. During the study period, 1185 machines were positioned across Stockholm inner-city, making them highly available, especially in the central areas.

Detailed transactions data for a two months period *Before* (April 1, 2013–May 31, 2013) and *After* (March 1, 2014–April 30, 2014) the introduction of the new parking policy were extracted and processed using R software environment. The time lag between policy implementation and the *After* analysis period (6 months) was designed to allow short-term behavioral changes to manifest and stabilize. The transaction data contains information on ticket id, enter and exit times, total fee and payment details.

Data concerning street blocks belonging to each of the three street categories was collected. Based on the vending machine coverage and while ensuring the spatial and street type coverage, 56 street blocks and corresponding vending machines were selected for this study. The sample rate is higher for those blocks that were subject to price changes where 137 out of the 150 parking spaces (91%) with high increase and 210 out of the 1500 parking spaces (14%) that have seen a low increased were measured in this study. The latter group consists of both *Arterials* and commercial streets in the *Extended city center*. The unchanged area includes the vast majority of the on-street parking spaces in the inner-city,

Table 2
Before and after weight factors by price group and time of day period.

Street category	Morning (07–11)		Midday (12–15)		Afternoon (16–19)	
	Before	*After*	*Before*	*After*	*Before*	*After*
High increase	1.00	0.79	0.98	0.77	0.98	0.77
Low increase	1.00	0.82	0.90	0.77	0.93	0.78
Price unchanged	1.09	1.03	1.03	0.99	1.04	0.98

of which 3.5% or 498 parking places were included in this study.

4.3.2. *Floating car*

Film data was collected through a floating car that is equipped with data logger and GPS system on the following dates: May 7 and May 22, 2013 and April 1 and 3, 2014. In total, 165 and 150 block-level parking load observations were obtained in 2013 and 2014, respectively. The car traversed each of the street blocks at least once per morning, noon and afternoon on both *Before* and *After* period. The films were then manually analyzed to record the number of parking cars per street block. Potential sources for discrepancy between floating car and vending machine data include alternative payment methods, residents with monthly tickets and groups that are exempted from paying parking fees, the parking duration issued in the ticket is longer than the actual parking time, illegal parking and tickets issued by cars parking elsewhere. Since these elements will result in either under- or overestimation of the parking occupancy it is not impossible to determine their overall effect a-priori. Moreover, some of these effects are expected to vary considerably over street blocks.

Other changes in the parking market might take place simultaneously to the introduction of the new parking scheme. For example, the City of Stockholm upgraded a new text messaging payment service. In order to control for the potential changes in the measurement ratios between vending machine data and the ground-truth, the former was calibrated separately for the *Before* and *After* periods based on the corresponding floating car data. Alternative travel choices may also change during the analysis period. In particular, no considerable changes in public transport and off-street parking supply took place between 2013 and 2014.

4.3.3. *Parking supply*

The corresponding parking supply database includes the total parking length available in meters which was then converted into number of vehicles based on an average vehicle length. On-street parking supply has not changed during the study period.

5. Results

The results of the analysis are presented and discussed in this section. First, the measurement ratios that have been obtained and then applied for calibrating the vending machine data are reported. Second, the average occupancy levels are reported for the before and after periods. Third, the temporal profile of occupancy level and the maximum occupancy level are investigated. Finally, we report changes in parking utilization performance in terms of duration, throughput and fare collection.

5.1. *Calibrating vending machine data*

As explained in the survey methodology section, the vending machine data was calibrated by comparing floating car data with the corresponding occupancy rates computed based on ticketing transactions. Note that the discrepancy between recorded transactions and the ground-truth can stem from residents who are parking permit holders, illegal parking, cars that parked shorter than the ticket is valid, users that use machines that are not directly adjacent to their parking block and users that paid using other payment methods, namely SMS service. While these different cases cannot be identified from the floating car data, their overall contribution to parking activities can be taken into consideration by weighting the ticket machine data accordingly for the entire study period. For example, car floating data in the *Before* period was available at 9:54 for one of the blocks along Fulkungagatan, one of the main arterials in the inner-city. The film data shows 14 vehicles parking there out of the 16 available parking spaces. In contrast, the number of parking vehicles obtained from processing the transaction data suggests that 12 vehicles park there at this time. Hence, the measurement ratio for this particular pair of parking data is 1.16. In order to allow a robust calibration, measurement ratios were calculated over a large number of observations.

Weight factors were calculated for six different street types based on their location, characteristics and pricing policy. Table 2 reports the measurement ratios, $\omega_{j,t}$, obtained for each survey period, price change category and time of day period. Weight factors in spring 2013 varied between 0.90 for the low price increase group during the midday period and 1.09 for the group where price remained unchanged during the morning period. This suggests that the aggregate occupancy rates obtained from the automatic machines closely replicates the ground-truth parking conditions for all street types in the *Before* period.

As evident in Table 2, this changes in 2014 as the data processed from the vending machines systematically underestimates the ground-truth occupancy by 13–21% on blocks where price has changed when compared with the *Before* period. This is presumably attributed to the increasing popularity of the above mentioned alternative payment methods. Interestingly, this trend was not observed for the control group where the data sources corresponded very well also in the *After* period. Sample variations are in the range of 0.03-0.18 for all price change categories and survey periods. These results suggest that the weights applied in this study per price category are fairly robust. Based on the results of this data processing phase, a weighting factor was assigned to each street block and time of day period to calibrate the respective datasets from fall 2013 and fall 2014.

5.2. *Average occupancy level*

Although location and price are inseparable, the difference in parking utilization between the *Before* and *After* periods can arguably indicate the impact of price on parking demand while using the simultaneous change for street blocks without price change as a reference. Fig. 3 shows the average occupancy rates for each price change category when averaged over all street blocks within each group *Before* and *After* policy implementation between 7:00 and 19:00. In spring 2013, the average occupancy rates did not vary much among the street blocks that were later subject to different price changes, ranging from 81% for the *Unchanged*

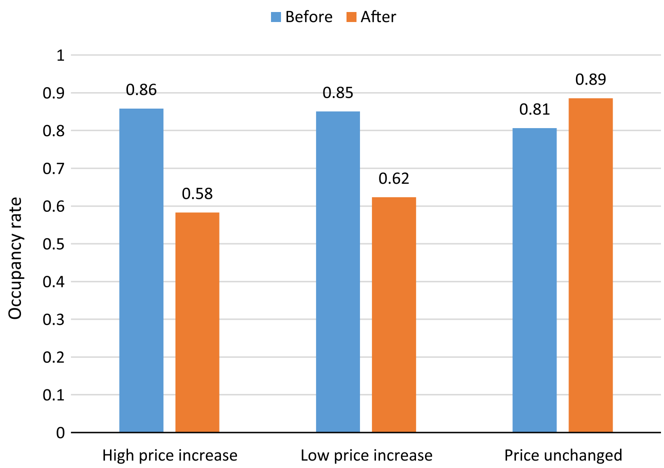

Fig. 3. Before and after average occupancy rates by price group.

to an uneven parking utilization over the day. Fig. 4 plots the average occupancy rate for each street block group over an average weekday *Before* vs. *After* the policy implementation. It is evident that the aggregate changes observed in Fig. 3 occur constantly throughout the day. All of the parking occupancy curves follow the same trend with a sharp increase in occupancy levels in 7:00–9:00 that ends with an abrupt decrease that is followed by a further increase (more moderate in the case of *Low increase* and *Unchanged*) until midday and then small fluctuations between 12:00 and 15:00 are followed by a gradual decrease. The fluctuations are caused by time lags in the exchange of outgoing and incoming flows.

The noticeable decrease at 9:00 is caused by the way the vending machine handles night parking. Tickets that are issued after 17:00 or 19:00, depending on the parking zone-when parking is cheaper or even free-are automatically defined to be valid until 9:00 on the following day. This data recording issue results with an inflated occupancy level between 7:00-9:00 but does not hinder the correct clearance of overnight parking from one day to the other and the integrity of parking balance. After discarding records before 9:00, the average maximum parking occupancy level for all street blocks occurs in midday, between 12:00 and 13:15.

Table 3
Before and after comparison of performance indicators.

Street category	Parking Duration [hour]			Throughput [veh/parking place/day]			Total Fare Collection [SEK/parking place/day]		
	Before	*After*	Diff. (%)	*Before*	*After*	Diff. (%)	*Before*	*After*	Diff.
High increase	2.36	0.80	−66	4.00	3.57	−12	185.5	117.0	−37
Low increase	2.38	2.20	−8	0.99	1.75	53	37.2	67.0	80
Unchanged	2.42	2.41	0	2.34	2.54	8	108.0	116.1	8

category to 86% for the *High increase* category.

A pronounced decrease in the average occupancy rate occurred on both categories that exhibited an increase in parking fees. Hence, it became easier to find a vacant parking space along these street blocks. The magnitude of the decrease in parking utilization corresponds to the degree of price increase. In contrast, the *Unchanged* category experiences a moderate increase of 8 percent in parking occupancy, resulting with an average occupancy rate of 0.89, higher than the initial level measured on the two price change categories.

5.3. Temporal variations and maximum occupancy level

While average occupancy levels are indicative of overall parking utilization, temporal variations in demand are expected to lead

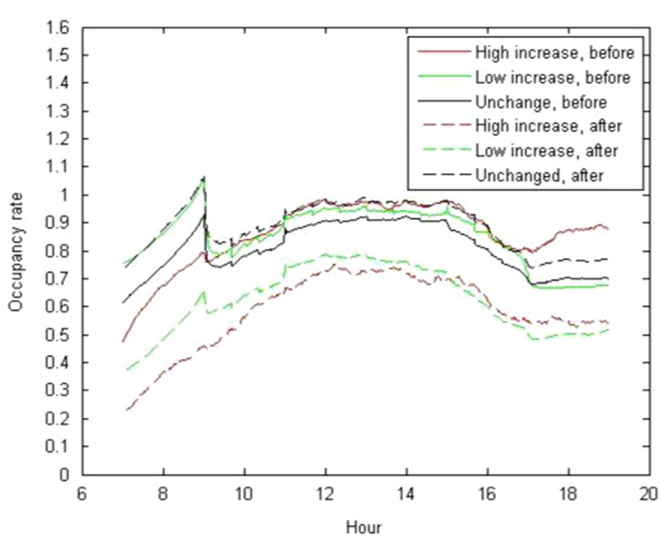

Fig. 4. Temporal variations in average occupancy rates by price group and time-of-day, before and after the policy implementation.

The average maximum occupancy level decreased considerably from an initial high level for street blocks that were subject to a price increase. In the *Before* period, the street blocks that were most highly taxes were also the most utilized with the occupancy rate approaching 100% during the peak hours – an average level of 95% occupancy was recorded during 12:00–14:00. This possibly reflects a small increase from the 90.9% occupancy level measured in the 2011 manual parking survey in the inner-city during midday (Stockholmsstad, 2013b). The maximum values of the parking occupancy curves of the *High increase* category in Fig. 4 are 0.97 (recorded on 12:01 PM) and 0.75 (12:16 PM) in the *Before* and *After* periods, respectively. The corresponding values of the *Low increase* category are 0.94 (1:02 PM) and 0.79 (12:05 PM). In contrast, *Unchanged* became the most heavily utilized category as the maximum occupancy level increased from 91% (1:03 PM) to 98% (1:01 PM).

5.4. Parking duration, throughout and total fee collection

A lower parking occupancy does not necessarily imply that fewer cars utilize the parking supply. Table 3 compares the average parking duration, daily throughput – the number of cars using a parking place on an average day-and the daily TFC from ticketing transactions per parking place. All of the performance indicators refer to the average value of the analysis period of 7:00-19:00. In the following we will compare the *Before-After* changes for different categories rather than comparing the absolute values because street categories are defined based on the price change that occurred and may be composed of various street types in terms of centrality, land-use etc.

It is evident that all parking measures of performance changed dramatically on those street blocks that were subject to a price increase, while remained almost unchanged where no price changes occurred. This suggests that the price change is the prime driver of behavioural change in parking habits rather than external factors. In particular, the composition of parking user groups (e.g. residents, commuters, shoppers) may change as a result of the price change. The average parking duration decreased from 142 and 143 min to 48 and 132 min for the *High increase* and *Low increase* categories, respectively. These results are in line with those of Ottosson et al. (2013). The corresponding percentage decreases for these two street types are 66% and 8%, while the parking duration on *Unchanged* remained at the same level.

The throughput and TFC manifest changes distinctively different from the change in parking duration. Compared with the *Before* period, the *Low increase* streets accommodate more vehicles and generate a higher revenue while *High increase* sees the opposite, although milder, effect. Throughout is the constantly the highest in the *High increase* category (3.5–4 vehicles per parking place per day) although it experienced a 12% decrease from 2013 to 2014. Hence, fewer cars parked for a shorter period on these street blocks resulting with a lower parking occupancy. This is also reflected in the 37% decrease in TFC as the higher parking fee per parking car did not compensate for the decrease in total parking hours. In contrast, both throughput and TFC on the *Low increase* observes increases. Throughput levelled from a low level of a vehicle per parking place per day prior to the price increase. The greater circulation and the higher fees resulted with a 80% increase in the TFC.

6. Discussion and conclusion

The impact of the pricing policy on parking performance and policy implications of this study are first discussed, followed by proposing directions for future research.

6.1. Policy implications

A parking pricing scheme targeting visitors to Stockholm inner-city is evaluated in this study based on a before-after comparison of parking utilization measures. We presented a method to systematically measure and analyze on-street parking. The results confirm that the price change was introduced on street blocks where the average maximum occupancy rate exceeded the desired occupancy rate of 85% between 10:00 and 16:00. The pricing policy fulfilled its objective to increase the ease of finding a vacant parking place in the central areas as average maximum occupancy levels decreased from an average maximum level of 95% down to 75%.

It hence led to a reduction in searching time and traffic caused by searching for a curbside parking.

The current pricing scheme is inadequate for obtaining the 85% maximum occupancy level objective. The average maximum occupancy levels on the street blocks that were subject to a price increase suggest that the current pricing scheme overprices parking on these blocks and therefore results with underutilized parking spaces. Moreover, average maximum occupancy levels increased beyond the desired level on the street blocks where price has not changed and is almost at capacity in its peak. This *Unchanged* category contains streets with different price levels with significant variations in occupancy levels. A closer investigation of the occupancy rate by price level suggests that the *City Centre* (*Red* zone) is oversaturated and approaches capacity whereas the maximum occupancy recorded in *Residential streets* (*Blue* zone) is in the range of 0.7–0.8. Prices in the *City Centre* streets should therefore be increased to relieve them for the current occupancy level and obtain a more efficient parking utilization.

The findings of this study concurrence that demand for parking exercises considerable temporal and spatial variations. The pricing scheme assessed in this paper was applied at both zonal- and street-levels and uniformly for a long time interval. New technologies facilitate the introduction of dynamic and variable parking prices that depend on actual and local demand levels. Prices can then be adjusted in order to obtain the desired parking performance levels. Note that parking management should consider a variety of parking indicators beyond the desired occupancy level, such as the throughput and access to visitors.

While average occupancy level can be indicative of overall parking performance, it is not indicative of the ease of finding a vacant parking space and its consequences for cruising traffic. It is therefore recommended to go beyond average occupancy levels when assessing policy implications and consider the likelihood of finding a vacant parking space which reflects passenger experience and relates to parking search externalities. The on-street parking search process could be simplified by considering a sequence of independent Bernoulli trials with the failure rate corresponding to the average parking occupancy in a given area. This implies that the probability that a certain number of blocks is traversed before finding a vacant on-street parking spot could be approximated based on the Geometric distribution. For example, the average number of blocks that need to be traversed in the central business district before finding an available parking place decreased from 6.67 to 2.38 following the introduction of the new parking scheme. This suggests yielding a substantial decrease in the contribution of cruising traffic to overall traffic flows.

6.2. Future research

The findings reported in this study refer to the short-term effects of parking price change on visitors to the urban centre. A follow-up study will enable the analysis of parking patterns once users are fully accustomed to the new price level. Further studies are needed to gain better understanding on various dimensions of parking decisions. In particular, assessing the overall demand for parking and the generation and substitution effects of parking pricing changes for different user groups. Future studies should analyze choice changes at the individual level in order to investigate the prevalence of parking user adaptation strategies (e.g. off-street, alternative on-street, parking duration adjustments, mode, departure time and destination choices) as the extent of behavioral adjustments depends on individual and trip characteristics (Kelly and Clinch, 2006). This will enable investigating the underlying trade-offs for different user groups and their implications on liveability and parking management strategies. The availability of individual identification in the vending machine data could facilitate such an analysis and enrich the results from a conventional survey.

The potential deployment of dynamic variable parking prices calls for research on optimal pricing techniques. Qian and Rajagopal (2014) formulated a real-time parking pricing policy based on real-time occupancy information as a stochastic control problem. Further research may investigate demand-anticipatory techniques to set dynamic pricing that optimizes policy objectives, including minimizing cursing traffic and considering the composition of user groups.

The joint effect of congestion and parking policies which was considered in analytical models but could be supported by empirical findings from cities where they coexist such as in Stockholm. Similarly to congestion charging, the equity implications of parking pricing should be further investigated.

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