From Modeling Parking Search to Establishing Urban Parking Policy

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The paper presents a conceptual view and explicit agent-based model of parking in a city. Driver-agents behave within a high-resolution GIS database of the street network and parking facilities. They drive towards their destination, search for parking, park for a given interval of time, and leave the network. During parking search, driver-agents estimate the availability of parking places, their price, and parking enforcement efforts, and decide whether to park or not. The model is implemented as an ArcGIS C#.NET application and is applied to the Tel Aviv central area.

1 Introduction

Parking policies have a strong impact on the behavior of drivers and, through it, on the functioning of cities. As such, they require careful analysis and evaluation at the level of a single driver. Against this background, we develop a spatially explicit Agent-Based model of parking in the city. The model enables the systematic analysis of the impacts of various policy scenarios, using a set of quantifiable data relevant to policy-makers.

The development of spatially explicit simulations of drivers' parking behavior is still in its infancy. The first attempts in this direction dealt with over-restricted situations of search and choice within an off-street parking lot (Harris and Dessouky 1997) or several adjacent street segments (Saltzman 1997). The model of Thompson and Richardson (Thompson and Richardson 1998) goes essentially further and considers driver parking search and choice between on-street and off-street alternatives in a realistic way. However, it still deals with a small abstract grid network of two-way streets. The recent model of Dell'Orco and Teodorović (2005) makes an essential step toward specifying drivers' parking behavior by means of a set of fuzzy rules. It does not account for relative location of parking facilities (and in this sense is not spatial), but the parking choice rules clearly describe how the driver-agent chooses between on-street legal/illegal and off-street parking with low/moderate/high fees based on distance to CBD, previous parking experience and planned parking duration. Using data on actual parking facilities, the model is applied to the city center of Bari (Italy), in order to establish appropriate parking fees.

While the above models provide deep insight into some key questions on parking, they cannot be directly applied to real-world settings and, hence, cannot be used to assess and evaluate real-world policy alternatives. The model developed in this paper aims filling the gap. It provides a realistic framework for investigating drivers' parking search and choice behavior within real cities. While the model is by no means fully developed yet, the first results do show that the approach enables analysis and assessment of a wide variety of parking policy scenarios within real-world settings.

2 The Setting: Parking Problems In Urban Settings

Virtually all cities in industrialized countries face parking problems, when defined as an imbalance between demand for and supply of parking, at least in specific areas of the city and during specific time intervals. This imbalance typically occurs around high-density employment centers during workdays or during peak shopping periods around shopping centers. Furthermore, older neighborhoods, especially in European cities, increasingly experience a tension between demand for residential overnight parking and available on-street parking supply.

Without appropriate parking pricing or severely restrictive measures, these types of areas will nearly always experience a situation in which demand for parking exceeds supply during at least part of the day. Moreover, due to synergetic reactions, parking problems in one area tend to spill over in another. For instance, visitors of bars and restaurants may park on-street in a neighborhood, decreasing the probability for local residents to find an on-street place for overnight parking. In reaction, these residents will extend their search area into surrounding neighborhoods, which will, in turn, face a growing imbalance between demand and supply (Shoup 2005).

Policy intervention thus becomes increasingly complex, as measures in one area and for a particular group of drivers (e.g. commuters) may worsen the conditions in another area and for another group of drivers (e.g. local residents or visitors). Since the typical goal of a municipal parking policy will be to guarantee a balance between demand for and supply of parking (i.e. a demand/supply ratio below, but close to, one), relatively small changes in parking demand or supply, due to e.g. increasing car ownership, densification of land uses, or changes in traffic arrangements, can easily result in an increase of the demand/supply ratio to a level above one. The impacts of parking measures thus become extremely difficult to forecast.

This "criticality" of the situation implies that a practically applicable tool for testing policy measures will have to explicitly represent the dynamics of the parking situation, based on precise estimates of demand and supply, at the spatial and temporal resolution at which policy measures could be implemented. Only in this way the 'on-street' competition between drivers looking for parking, each faced with the aforementioned synergetic system reactions, can be accounted for. In

other words, we need a spatially explicit agent-based model of parking search in the city, in order to analyze, and ultimately tackle, parking problems in cities in highly motorized Western societies.

3 The Simulation Model of Parking in the City

To adequately represent the processes of parking in the city, we build on high-resolution infrastructure GIS, which are in use for an increasing number of cities around the world.

3.1 Infrastructure GIS

Four components of the model GIS are either directly obtained from or constructed on the available infrastructure GIS of a city (Figure 1).

Road network contains information on traffic directions, turn permissions, parking permissions, fees, and probability and size of parking fines, for each on-street parking segment. The centerline of the two-way streets is duplicated in order to visually represent cars driving in both directions.

Destinations are associated with the features of three layers – Dwellings, Offices/Public places, and Open spaces. In case several destinations of different types are located in one building, the destination point is multiplied. Destinations' attractiveness for different groups of drivers is estimated based on the number of apartments in a building, or type and size of the enterprise, public place or open space (small, medium, large).

Off-Street Parking Places are associated with houses and parking lots. The number of off-street residential private parking places is an attribute of the building. Public parking lots are organized as a separate GIS layer and are characterized by capacity and price.

Road cells and on-street parking cells are employed for driving and parking, respectively. They are constructed by dividing the street segment centerline into P-meter fragments (in Tel Aviv, according to the field survey, P = 4). A "road cell" is just this fragment of the centerline, while "parking cells" are set at a given distance of the centerline (Figure 1). The attributes of an on-street parking place are parking permission (including 'parking not allowed'), fees, and the probability of a fine for illegal parking per hour.

Figure 1: To represent a two-way traffic street, the centerline is duplicated, and each copy is employed for representing one direction. Parking places are built parallel to the street, with a distance of 4 meter between the places. Destinations are represented by the set of points constructed in front of the entrance to the building (red triangles in the map).
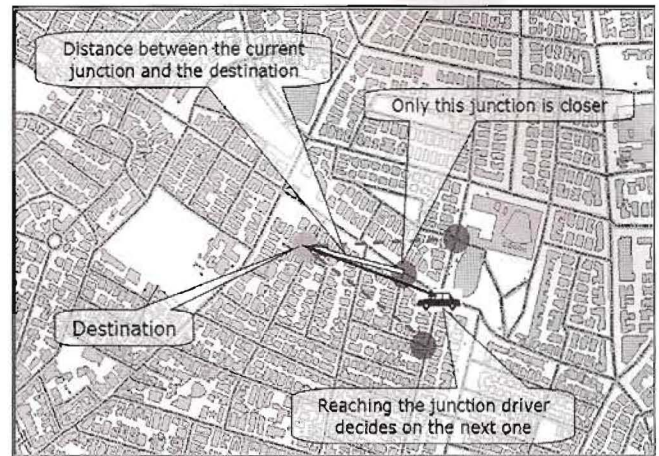

Figure 2: Driver's choice of direction at a junction.

3.2 Driver agents and their behavior

We distinguish between four groups of drivers: Resident, Employee, Customer, and Guest. They differ in terms of typical destinations, arrival time and parking duration.

The essence of the agents' representation is their parking behavior. Full description of drivers' behavior should include: (1) driving towards the destination before reaching parking area; (2) driving within parking area, while searching for parking; (3) parking; and (4) driving out. We focus on the second and third stages of drivers' behavior. We assume that each model driver has its own destination (assigned during driver's initialization). Based on field surveys, the parking search area is currently set as a network service area with a 250 m radius. The driver enters the model by "landing" at a random point at the outer boundary of the parking search area, which is automatically calculated based on the assigned destination. Then the car drives towards the destination while searching for parking and, if succeeding to find a parking place, parks for a pre-set interval of time. We thus ignore driving towards the parking search area and erase the driver from the system directly after parking duration is completed.

Based on (Carrese, Negrenti et al. 2004), we assume that the driving speed during the parking search is 12 km/h, no matter what was the speed before. This and the majority of other parameters of drivers' behavioral rules are based on field surveys, but some are still based on commonsensical knowledge regarding parking behavior. Current parking choice rules are tuned to the Tel Aviv situation, in which on-street parking is substantially cheaper than off-street parking.

Driver's choice of street segment. Generally, when arriving at a junction, the driver selects the segment which takes her closer to the destination (Figure 2). We have verified this algorithm driving with several drivers (all Tel Aviv residents) and, in addition, investigated that in case the destination is at a distance of 3-5 street segments from the current junction (typical for driving within parking search area), the algorithm usually repeats the shortest path to the destination.

Driver's decision to park on the way to destination. Driving towards the destination, a driver registers the fraction of free parking places and, depending on her estimate of the distance to destination, estimates the expected number F of free parking places on the remaining route to the destination. Each time the driver passes a parking place, she re-estimates the fraction of free parking places and, based on it, the expected number of free parking places ahead. When passing a free

parking place, the driver decides whether to park or continue driving towards the destination. The decision depends on the value of F: the driver continues driving towards the destination if $F > F_2 = 3$, parks immediately if $F < F_1 = 1$, and continues driving with the probability $p = (F - F_1)/(F_2 - F_1)$ in case $F_1 \leq F \leq F_2$.

Besides instantaneous re-estimating of F, the driver "remembers" several (parameters of the model, usually 4) of the latest street links she has passed during the parking search. The driver tries to avoid using these links when arriving to the junction and deciding on the link to turn to; if impossible, she prefers the link visited least recently. We admit that the knowledge of the local road network and the parking experience in the area can differ between, say, the residents of the area and the visitors, but due to lack of data do not account for drivers' long-term memory in the current version of the model.

Driver's decision to park after missing destination. The model driver who has passed her destination without parking, changes the decision rule, and is ready to park anywhere as long as it is not too far from the destination. We assume that, initially, the driver is ready to part at a distance of 100m or less form the destination, and that this area grows at a constant rate (currently 0.25 m/sec). When reaching 250m, the expansion of the area stops.

When failing to find an on-street parking space for a „very long time" (currently 10 minutes) the model driver quits searching for on-street parking, drives to the closest paid parking lot and parks there. The driver remains at an on-street parking place or in a parking lot during the pre-set agent's parking duration. Then she vacates the parking place and disappears from the system.

3.3 Technical Characteristics of the Model
The model iteration is 0.5 sec - the time necessary to pass the 4m interval at a speed 14.4 km/h. We employ sequential updating and consider all moving cars in a random order, established anew at every iteration. Depending on car's speed, the number of road cells that should be passed is calculated and rounded to one of two closest integers proportionally to the fractional part of the result. If one of the road cells that should be passed is occupied by another car, the advance is interrupted and limited to the previous cell(s).
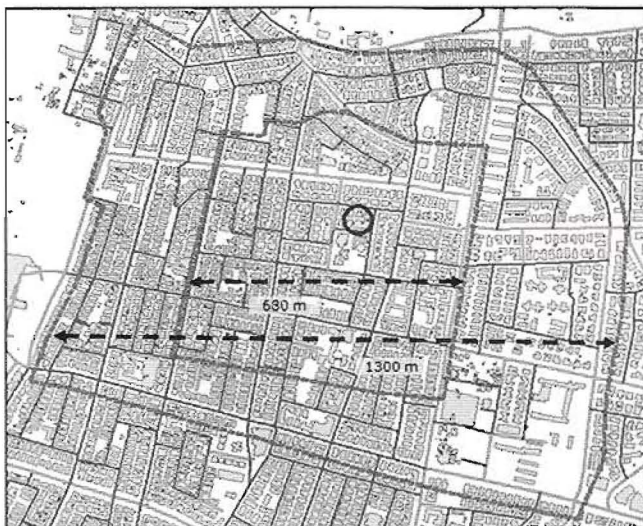

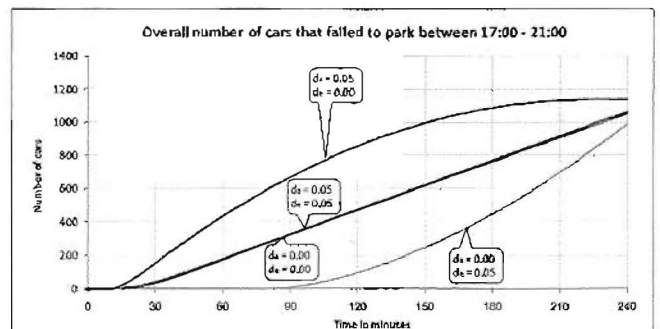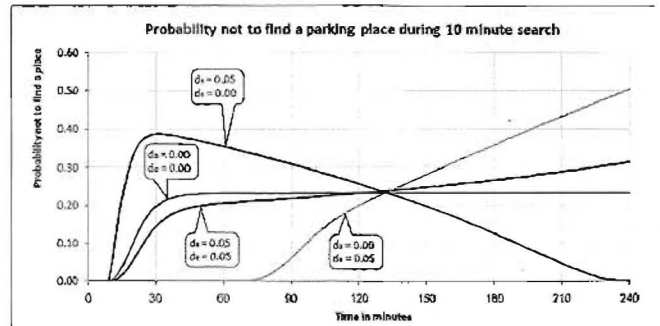Figure 4: Snapshot of the model map screen with two areas around the new parking lot.

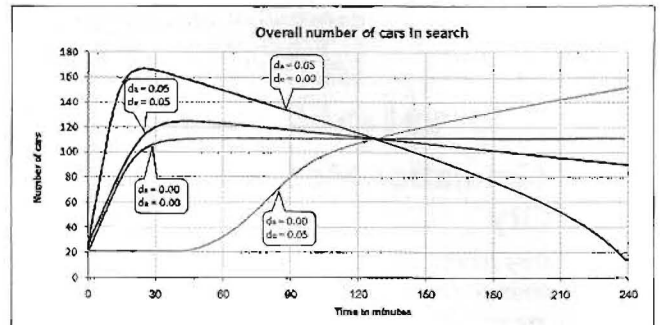

Figure 3: The dynamics of the (a) overall number of cars searching for a parking place C(t); (b) fraction of cars that fail to find a parking place F(t)/a; (c) accumulated number of cars that failed to find a parking place for $d_a = 0.00$, 0.05 and $d_e = 0.00$, 0.05. The time interval is 17:00-21:00h.

The model is implemented as a C#.NET *ArcGIS™* application and its performance remains high for several thousands of simultaneously parking drivers. The latter is sufficient for theoretical and practical implementations.

3.4 Policy performance indicators
The object-based nature of the model enables following every driver and, thus, direct estimation of the performance of a parking policy from the driver's and the policy-maker's point of view. Given the city area and time interval during the day, we focus on distributions of several indicators which reflect the drivers' and policy-makers view of the system. From the driver's point of view, the indicators include estimates of the distribution of parking search duration, walking distance between parking place and destination, and parking costs. To reflect the policy-maker's point view, we consider the dynamics over time of the fraction of occupied parking places and the number of cars searching for parking, parking turnover during the modeled period, and the revenues from on-street parking and paid parking lots.

4 Experimental Estimates of Parking Demand and Supply

We have applied the model to explore a number of parking policy scenarios for the Basel neighborhood in Tel Aviv (see below). The Basel neighborhood is a typical residential area in the old center of Tel Aviv and is characterized by a high density and a mix of land uses. It has a size of about 1.5 km² (Figure 4).

Data on parking demand and supply in the neighborhood are essential input for the model. Especially in cases where the demand/supply ratio is above one, as in the Basel case, detailed data, on the types of drivers, parking duration and destinations, are a necessary prerequisite for modeling parking dynamics. Furthermore, since the demand/supply ratio will change over time as a result of arriving and departing cars, parking arrival and egress rates over time are also crucial model input. In order to estimate the demand and supply of parking places at this detailed level of resolution, we have performed several field surveys.

The majority of the data were collected during loop trips over selected streets in the Basel neighborhood, at different hours of the day or at night, and on the different days of the week. Every time the surveyors passed a street segment, they recorded the exact location of every parked car, its plate number and parking permissions as exhibited on the car window. These data made it possible to estimate the duration of parking and to distinguish between different groups of drivers (e.g. residents and visitors of the area).

The residents' demand for parking in the area was estimated on the base of the number of residential units and municipal data on the number of parking permission received by residents. The parking demand of employees and visitors was estimated on the base of the GIS data on building use. The duration of the unsuccessful search was estimated on the base of a survey performed at the entrance of a paid parking lot in the center of the neighborhood.

Table 1 presents the estimates of overall parking demand and supply in Basel the area. As can be seen, the overall demand/supply ratio in the area is about 1.12. However, the situation is different at the end of the day, as about 60% of the available parking places in the area remain occupied by area residents during working hours. This implies that the drivers of about 4,000 cars arriving back to the area at the end of the day face an average demand/supply ratio about 1.35. Note that the chance to find an on-street parking place in the area is relatively high for drivers arriving back home early (around 17.00h), but quickly decreases over time. As a result, an essential number of drivers that arrive late in the neighborhood will search in vain for free on-street parking for a relatively long time (5-10 minutes according to the survey results), and then park at the paid parking lot.

It is worth noting that despite the severe lack of the on-street parking places, drivers avoid parking far from their home address. To estimate the "acceptable" distance between on-street parking place and driver's home address, we have recorded the plate numbers of about 800 cars parking in the Basel neighborhood during two consecutive nights, and compared the cars' location to the car owners' addresses through the Israeli Central Bureau of Statistics. Combining both datasets, we estimated that the vast majority of the cars recorded in the survey parked not further than 250 m air distance (5 minutes walk) from the driver's residence. We thus concluded

that, despite the lack of parking space, residents continue their parking search either till they find an on-street parking place at an acceptable distance from their home, or, if failed, park at a nearby paid parking lot.

5 Rough Estimates of Parking Success

Before employing the model to analyze the parking situation in the Basel neighborhood, it is worthwhile to explore, in a theoretical sense, what might be the outcome of the parking situation described in the previous section. As mentioned there, the Basel neighborhood faces an essential shortage of supply for overnight residential parking. In what follows, we shortly consider an a-spatial ecological-like model, which provides insight into how the competition between drivers will work out in the evening, when the only possibility of parking for the arriving driver is to capture the parking place vacated by another driver. The non-spatial nature of the model does not allow estimating the distance between the parked car and the destination.

To investigate the parking dynamics in real-world settings, let us provide some rough estimates of the parking search time in the simplest and most abstract settings. Let us assume that cars arrive to a specific area at a certain arrival rate $a(t)$ (cars/Δt) in order to find a parking place, and that cars already parked in that same area leave at an egress rate $e(t)$ (cars/Δt). Let us also assume that the maximal driver's search time is $n*\Delta t$, and that the driver leaves the area if failing to find a parking place during this time. Let us ignore the spatial dimensions of the area and estimate the probability that the car arriving at $t - n*\Delta t$ would fail to find a parking place until t.

Below we consider the process as starting with all parking places occupied at $t = 0$.

Let us denote as $C(t)$ the overall number of cars in the system, as $N(t, t - k*\Delta t)$ the number of cars that entered the system at $t - k*\Delta t$ and are still searching for the parking place at t, as $p(t)$ the fraction of cars that fail to find a free parking place between t and $t + \Delta t$, and as $F(t)$ the number of cars that leave the system just after t.

Note that $F(t) = N(t, t - n*\Delta t)$ and $p(t) = 1 - e(t)/C(t)$.

The dynamics of $N(t, t - k*\Delta t)$, and $C(t)$ can be represented by the following simple system of equations:

$$C(t + \Delta t) = C(t) - F(t) + (a(t) - e(t))*\Delta t,$$
$$N(t + \Delta t, t) = a(t)*p(t),$$
$$N(t + \Delta t, t - \Delta t) = N(t, t - \Delta t)*p(t)$$
$$N(t + \Delta t, t - 2*\Delta t) = N(t, t - 2*\Delta t)*p(t)$$
$$...$$
$$N(t + \Delta t, t - (n - 1)*\Delta t) = N(t, t - (n-1)*\Delta t)*p(t)$$

Note that the number of cars that fail to find a parking place in a real city is always higher than $F(t)$, as we do not account for the distance between the car searching for parking and the parking place that becomes free and assume that the latter is occupied immediately by one of the cars searching for parking at that moment.

Figure 3 presents the dynamics of the overall number of cars in the system $C(t)$, the fraction of the cars that failed to find a parking place $F(t)/a(t - n*\Delta t)$, and the accumulated number of cars that failed to find a parking place for the constant and linearly decreasing arrival and egress rates during the time interval 17:00-21:00h. We assume that $\Delta t = 1$ min and $n = 10$ and base overall arrivals and egresses as obtained for

the Basel neighborhood. According to Table 1, about 5,000 cars are arriving to the neighborhood during four evening hours and about 4,000 visitors' cars leave. This results in an average arrival rate am ≈ 5000/(4*60) ≈ 20.8 cars/min and an average egress rate em ≈ 4000/(4*60) ≈ 16.7 cars/min.

We imitate the evening decay in arrivals and egresses by assuming that a(t) and e(t) decrease linearly from 17:00h till 21:00h as follows:

$a(17:00) = a_m + 120*d_a, a(21:00) = a_m - 120*d_a,$

$e(17:00) = e_m + 120*d_e, e(21:00) = e_m - 120*d_e,$

where d_a(cars/min^2) and d_e(cars/min^2) are the decay rates of arrival and egress respectively. We present four curves for d_a = 0.00 and 0.05 and d_e = 0.00 and 0.05. Note that we assume in the theoretical calculations that there are no free parking places at 17:00h and the number of cars searching for parking at 17:00h is zero.

The results show that the probability not to find a parking place changes over time and is highly dependent on the decay rates of arrivals and egresses. Over the whole time interval, the average probability not to find a parking place within 10 minutes is ~ 24%, irrespective of the decay rates. Note that, since we do not account for space in this theoretical model, this is the lowest possible probability given the real-life access and egress rates for the Basel neighborhood.

6 Application of the model to the Basel Neighborhood

As experimental data and theoretical estimates demonstrate, the drivers arriving to the Basel neighborhood in the evening have very few opportunities to find free on-street parking and a substantial number will cruise in vain to find a free parking place. Consequently, real estate developers are interested to build parking facilities and sell individual parking places to residents. Since the Tel Aviv Municipality has the authority to grant a building permit for such facilities, the municipality has requested us to analyze whether the construction of additional parking facilities would lead to a reduction in the parking pressure in the Basel neighborhood.

Basically, the municipality is in favor of constructing as large a garage as possible. In this way the parking pressure for residents (Table 1) will be eased and the number of residents' complaints about parking could be reduced. The private developer of the parking garage, in contrast, wants to be certain that the supply of parking places in the new garage will not exceed the demand and the price of a parking place would not decrease below the construction costs. She will therefore prefer to limit the number of parking levels, unless a proven demand exists. The challenge for both parties is to assess the possible demand among local residents for paid, reserved, off-street parking places in the new garage.

Based on the data in Table 1, we studied a series of scenarios, in which the capacity is set to 150, 200 and 250 places, as in the variants considered by the municipality. The simulations aimed at estimating the influence of additional parking places on the drivers whose destination lays in each of two concentric street blocks around the new parking garage (Figure 5). We investigated the critical period between 17:00-21:00h on weekdays.

As one could expect given a parking shortage of more than 1,000 parking places, even 250 additional places do not result in a substantial change in the parking situation in the area. According to the model results, the influence of the new garage can be felt within the central area only (Figure 4; NBH1), where the demand currently exceeds supply with ~350 places. Even with the maximal capacity of 250 parking places, the mean search time in the central area decreases only from ~6 to ~5 minutes, while average distance between parking place and residence decreases from ~160 to ~130 meter. Both improvements are small and will be hardly felt by the drivers. At the same time, the fraction of the drivers who do not succeed to park after 10 minutes search time is essentially reduced: the share of this group drops from ~35% in the existing situation to ~20% when the maximum of 250 parking places is added. These figures coincide with the theoretical estimates of ~ 24% (above) and ~17% (obtained for the number of arriving cars equal to 4750 instead of 5000), but – in line with expectations – are substantially higher as a result of the impact of space. These differences between spatial and non-spatial versions of the model manifest that the account of the real road network, traffic and parking conditions, might be critical for adequate assessment of the parking policy measures in the city.

7 Conclusion and Discussion

In this paper, we presented an Agent-Based, spatially explicit, model of parking in the city and consider some theoretical estimates that regard the same phenomena. In the simulation model, drivers' parking search behavior is presented in details within a high-resolution GIS of a city. The model is able to generate outputs relevant for both drivers and policy-makers and can thus be used as a tool to compare and evaluate various parking policies. We consider as substantial the model's

Table 1: Residents' overnight and end-of-day demand for, and supply of, on-street parking places within: NBH1, NBH2 excluding NBH1, and entire NBH2.

Characteristic		Part of Basel neighborhood		
		NBH1	NBH2 excluding NBH1	Total
On-street supply of parking places*		3751	7134	10340
On-street parking demand		3943	7678	11621
On-street demand/supply		1.11	1.13	1.12
17:00 – 21:00	On-street supply*	1313	2497	3810
	On-street parking demand	1693	3398	5091
	On-street demand/supply	1.29	1.36	1.34

*The calculation of the resident's overnight on-street parking supply encompasses 95% of the total amount of on-street parking places, as 5% of parking places are used by overnight visitors.

potential as a decision-making support tool in the field urban parking management.

Further research will be necessary to develop the potential of the model. The most important challenge lies in the development of the rules underlying drivers' behavior. The current rules are incomplete and only suitable for analyzing the case of free on-street and expensive off-street parking. In order to analyze other situations and explore a wider variety of parking policy scenarios, a more general set of behavioral rules with regard to parking search and choice is necessary. This will require additional collection of empirical data and extensive testing. Furthermore, a more realistic representation of drivers' behavior would require the introduction of driver's learning capacities into the model.

A more robust set of behavioral rules will subsequently allow further theoretical and empirical explorations. On a theoretical level, this includes the impact of driver heterogeneity on parking dynamics, as well as the importance of spatial heterogeneity on the emerging patterns of parking (Arnott 2006). At the empirical level, the model can be used to explore the dynamics between different driver groups (e.g. residents, visitors and commuters), the impacts of price versus regulative parking policies, the impact of enforcement measures on parking behavior, etc. Together with the extension of the empirical basis of the model, studies into these questions would generate a deeper insight into the model's abilities as well as its limitations.

Acknowledgements

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