The page numbers in this pdf are wrong, the reference should be K. Martens, I. Benenson, N. Levy, 2010, The Dilemma of On-Street Parking Policy: Exploring Cruising for Parking Using an Agent-Based Model, In B. Jiang, X. Yao (eds.), Geospatial Analysis and Modelling of Urban Structure and Dynamics, GeoJournal Library 99, Springer Science Business Media B.V., pp. 121-138

Chapter 7
The Dilemma of On-street Parking Policy: Exploring Cruising for Parking Using an Agent-based Model

Karel Martens[1], Itzhak Benenson[2] and Nadav Levy[2]

Abstract Virtually all major cities around the world face severe parking problems in their centers. While existing models of parking search and choice behavior do provide insight into the basic dynamics of parking in cities, as well as into the phenomenon of drivers cruising for on-street parking, virtually all models discussed in the literature ignore a number of key factors that influence parking behavior and parking dynamics. This paper makes a first step in this direction, by proposing a non-spatial model of parking search and an explicit geosimulation model of the parking process, termed PARKAGENT, which accounts for street network, drivers' decisions and their destination. We employ both models to analyze the phenomena of cruising for parking and compare the models' outcomes, focusing on the impact of space on parking dynamics. We estimate the main characteristics of these dynamics, and specify the conditions under which spatial effects are, or are not, important for analyzing parking. In particular, we demonstrate that traffic engineers' recommendation that about 15% of all on-street parking places should remain vacant to ensure easy ingress and egress and prevent cruising for parking can be decreased to 10% and even less, especially in case of relatively low parking turnover levels. The paper ends with a short discussion, in which we explore the implications for parking policies.

Keywords Agent-based Modeling, Transportation Modeling, Parking Modeling, Parking Search, Cruising for Parking

[1] Radboud University Nijmegen
[2] Tel Aviv University

B. Jiang and X. Yao (Eds.) *Geospatial Analysis and Modeling of Urban Structure and Dynamics*

7.1 Introduction

Virtually all major cities around the world face severe parking problems in their centers. In most cases, on-street parking is used to capacity throughout the day, and often even exceeds capacity as a result of illegal parking and double parking (Arnott, 2006). Different user groups, such as commuters, often occupy a large share of available parking space, to the detriment of other groups like visitors or residents. Moreover, the tension between demand and supply, in combination with cheap on-street parking, often results in an underutilization of available off-street parking facilities during large parts of the day and to high levels of cruising for cheap on-street parking (Shoup 2004; Shoup 2006).

While existing models of parking search and choice behavior do provide insight into the basic dynamics of parking in cities, as well as in the cruising phenomenon, virtually all models discussed in the literature ignore a number of key factors that influence parking behavior and parking dynamics. Arnott (2006, p. 469) stresses that the new generation of parking models should be able to deal with 'the complications caused by heterogeneity among travelers (especially with respect to the value of time, parking duration, and distance traveled), the inhomogeneity of downtown space, congestion interaction between cars and mass transit, parking by downtown residents and delivery vans, through traffic, and the endogeneity of parking duration'.

This paper makes a first step in this direction, by comparing the aggregate and non-spatial view of parking search with an explicit geosimulation view (Benenson and Torrens 2004) of the parking process. The geosimulation model accounts for three major system components: two representing urban infrastructure (street network and destinations) and one representing urban agents (drivers searching for parking). We focus on the impact of space on parking dynamics, estimate the main characteristics of these dynamics, and specify the conditions under which spatial effects are or are not important for analyzing parking. Geosimulation of the parking process is done with an agent-based model of parking behavior (Benenson, Martens et al. 2008; Benenson and Martens 2008; Martens and Benenson 2008). The impact of space is explored for the case of so-called commercial parking: short-term (an hour or so) parking in a city center by customers and business relations close to services and shops.

The paper is organized as follows. First, we provide a brief overview of existing approaches to modeling parking in the city and assess to what extent these approaches are able to deal with (i) the inherently spatial nature of the parking process, and (ii) driver's reaction to the changing local situation during parking search (Section 2). We then briefly present PARKAGENT, an agent-based model to simulate parking search and choice in the city (Section 3). In Section 4, we present a non-spatial (point) model of parking. In the point model, space plays no role at all in that drivers do not have to search for parking, but can directly occupy a free parking place, if it exists. This model serves as the base line against which we compare the PARKAGENT results. In Section 5-7, we analyze searching and cruising for commercial parking in an abstract rectangular two-way street network, using PARKAGENT. We demonstrate the effects of space that cannot be recognized in an aggregate model and show that these effects diminish in case the arrival rate is more than ~1.1 times the egress rate. The paper ends with a short discussion, in which we explore the implications of the obtained results for establishing urban parking policies.

7.2 Parking models

Various types of models have been developed to simulate and analyze drivers' parking behavior in urban settings. An elaborate review can be found in Young et al. (1991) and Young (2000). For our purposes, the models of parking can be distinguished in terms of their level of aggregation, as well as in their theoretical or applied orientation. In terms of aggregation, a distinction can be made between models that consider groups of drivers and those which explicitly consider individual drivers, and between those considering space implicitly in the stage of model formulation only and those explicitly simulating drivers' movements in space.

One side of the parking modeling spectrum represents spatially implicit and aggregate models. *Dynamic* models of this kind are mostly associated with the economic view of the parking processes (e.g. Arnott and Rowse 1999; Arnott 2006; Shoup 2006; Verhoef et al. 1995). These models provide deep insights into the persistence of urban "parking pattern" dynamics and are the necessary "litmus tests" for parking management in the real city.

The most important input of economic models lies in the systematic analysis of the interrelationship between parking conditions and parking policy. This results in the identification of sets of conditions and policies that optimize parking utilization based on peak hour traffic flows, departure time, modal split and so on (Arnott 2006; Andersson and Palma 2004; Calthrop and Proost 2006; Zhang et al. 2007; D'Acierno et al. 2006; Petiot 2004; Wang et al. 2004). Necessary for the analytical investigation, the regular economic assumptions of perfectly rational and utility maximizing behavior limits extrapolation of the models' conclusions towards real-world situations. E.g. Shoup's (Shoup 2006) model does not include space as it eliminates walking distance to the destination. Hence, Shoup can conclude that if prices of on-street and off-street parking are the same, the equilibrium cruising time is zero. However, if off-street parking is relatively sparsely scattered, and destinations are scattered over space, the decision to cruise depends highly on the walking distance between the closest off-street parking facility (assuming it is always available) and the destination.

The other side of the modeling spectrum – that of spatially explicit simulations of drivers' parking search and choice – has started in the 1990s and is still in its infancy. The models we are aware of deal with intentionally restricted situations of search and choice, e.g. parking search within an off-street parking lot (Harris and Dessouky 1997) or several adjacent street segments (Saltzman 1997). These explicit simulations consider parking behavior of drivers as a set of sequential events, in which drivers respond to the actual traffic situation. In principle, these dynamic models are capable of capturing the self-organization of the cruising phenomenon with a changing balance between parking demand and supply (see Shoup 2006 for a spectacular presentation of the problem), but the latter demands a substantial extension of the spatial dimensions of the models and an essential generalization of driver’s behavioral rules.

The only attempt in this direction we are aware of is presented in a paper by Thompson and Richardson (1998). They consider driver's parking search and choice between on-street and off-street alternatives within a small (twenty street segments of about 50 meter length), but realistic, grid network of two-way streets. The model is developed to follow one driver searching for parking within a fixed parking environment (i.e. no other drivers park or egress during this search). Nonetheless, the paper clearly demonstrates that optimal parking search behavior is hardly possible. Namely, the information available to the driver during parking search and choice is local in nature and long term experience does not necessarily lead to better choices. The outcome of parking processes in a spatially explicit model may thus be removed quite far from those obtained in economic models growing from perfectly rational drivers.

The above brief review leads to the conclusion that, while providing deep insight, most of the existing models cannot be used to formally assess the spatial effects of parking search. The models that potentially do provide these opportunities – spatially explicit and disaggregate models – are still underdeveloped and none of them can be employed to systematically assess the real-world situation of many drivers simultaneously searching for on-street and off-street parking, and simultaneously entering and leaving parking places in a realistic urban environment. This paper aims to start filling the gap by employing a recently developed, agent-based, GIS-based, model of parking in the city.

7.3 The PARKAGENT model

PARKAGENT is a spatially explicit, agent-based model of parking search and choice in the city. The model links a geosimulation approach to a full-fledged GIS database, which are in use for an increasing number of cities around the world. In this way, PARKAGENT enables a representation of driver’s parking behavior in a real-life city and in-depth analysis of the global consequences of driver's inherently local view of the parking situation.

7.3.1 Infrastructure GIS

Four components of the model GIS are either directly obtained from, or constructed on, the available infrastructure GIS of a city (Figure 7.1).

Road network contains information on traffic directions, turn permissions, parking permissions, fees, and probability and size of parking fines, for each street segment.

Destinations are associated with the features of two layers: Buildings and Open Spaces. The features of these layers can simultaneously have several uses, e.g. a building can be used for dwelling and for offices. Each use is characterized by capacity, which reflects the number of drivers that can use this feature as a destination. For example, a building's dwelling capacity of ten and workplace capacity of three means that ten residents can choose it as a destination when driving home after a working day, while three workers can choose it as a destination when driving in the morning to the workplace. 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). Open space destinations (parks and gardens) are also characterized by their capacity in respect to the number of drivers that can choose it as a destination.

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. Road cells are constructed by dividing the street segment centerline into fragments with the length of an average parking place (in Tel Aviv, according to the field survey, the average length of a parking place is 4 meter) and employed for representing driving. One (for one-way street) or two (for two-way street) "parking cells" are set parallel to the road at a given distance of the centerline (Figure 7.1), depending on the physical possibility to park at one or both sides of the street. The layers of the road cells and on-street parking cells are built by PARKAGENT based on the layer of streets; the attributes of the road cells and on-street parking places are transferred from the street layer. These are traffic direction, turn restrictions, parking permission (including 'parking not allowed'), fees, and the probability of a fine for illegal parking per hour.

PARKAGENT is a generic model and can be applied to any real (Figure 7.1a) or imaginary (Figure 7.1b) city given that the layers above are available. It also contains tools for constructing artificial street networks, as has been done for the purpose of this paper and shown in Figure 7.1b.

(a) (b)

Fig. 7.1 View of the PARKAGENT map window for (a) a real city; and (b) the abstract grid network. Blue points represent road cells, small single black points represent on-street parking places and larger attached black points represent parked cars.

7.3.2 Driver agents and their behavior

PARKAGENT is an agent-based model. This means that every driver in the system is assigned a specific origin, destination and form of behavior. A full description of drivers' behavior should include: (1) driving towards the destination at a large distance from the destination (before searching for parking actually commences); (2) driving in proximity to the destination, while searching for parking; (3) parking choice; (4) parking; and (5) driving out. PARKAGENT simplifies the first stage of driver's behavior and focuses on the other ones.

The initiation of a driver in the model begins with assigning the destination and desired parking duration. Then a network service area of 300 m radius is constructed for the driver's destination, consisting of a set of road cells at the boundary of this area, from which the destination can be reached after a 300 m drive. The driver enters the model by "landing" randomly at one of these cells, that is, we ignore driving towards the parking search area. Then the car drives towards the destination while searching for parking and, if succeeding to find a parking place, parks for the time interval assigned during initiation. We erase the driver from the system directly after the parking duration is completed.

Based on Carrese et al. (2004), and our own observations while driving with the drivers and recording their activities, we assume that the driving speed during the parking search stage is 12 km/h, no matter what the speed was before. At each road junction, a driver chooses the street (from those permitted) whose next junction is closest to the destination (Figure 7.2). Following this rule, the model driver usually takes the shortest path from the road cell they "land" on to her destination.

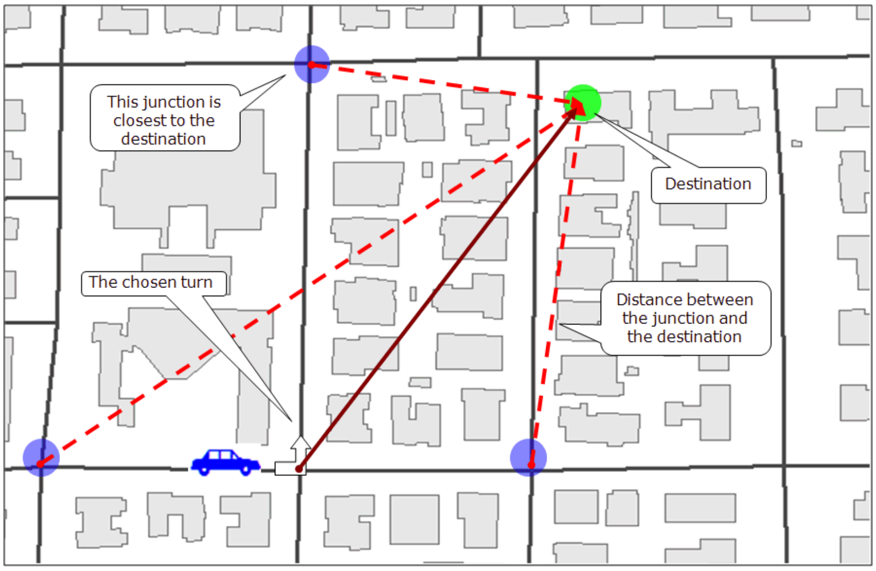


Fig. 7.2 Schematic representation of the driver's choice of the street segment (Benenson et al, 2008).

On-street parking in Tel-Aviv is substantially cheaper than off-street and in this paper we assume that every driver tries to find an on-street parking place before parking in a for-pay off-street parking facility.

Driver's decision to park on the way to destination

Driving towards the destination from the place of "landing", a driver registers free and occupied parking places at both sides of the road. Then, depending on her estimate of the distance to the destination, the driver estimates the expected number, F, of free parking places *on the remaining route* to the destination. Based on F, 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 as follows (Figure 7.3): The driver

- Continues driving towards the destination if $F > F_2 = 3$,
- Parks immediately if $F < F_1 = 1$,
- Continues driving with the probability $p = (F - F_1)/(F_2 - F_1)$ if $F_1 \leq F \leq F_2$.

Besides instantaneous re-estimating of F, the driver "remembers" several of the latest street links she has passed during the parking search (in the current version of the model, the driver remembers two recent links). The driver tries to avoid using these links when arriving to a junction and deciding which street 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 drivers, but we do not account for drivers' long-term memory in the current version of the model.

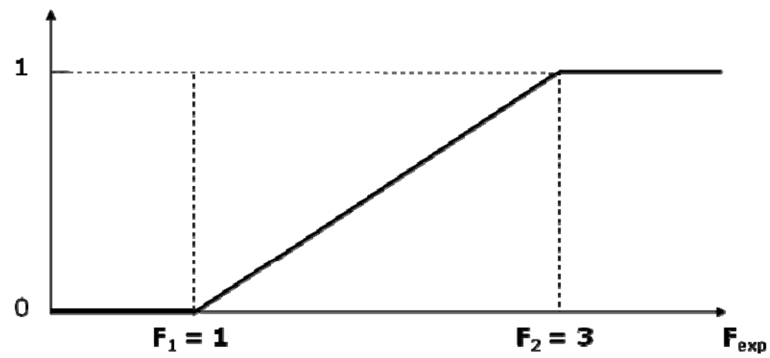


Fig. 7.3 The probability to continue driving when passing a free parking place as a function of the expected number of free parking places between driver's location and destination (Benenson et al., 2008).

When a driver parks *on the way to the destination*, we consider cruising time to be zero ($T_{cruising} = 0$). Obviously, in a real-world setting, drivers slowing down to search for parking *before* reaching their destination may also be perceived to be cruising for parking. Certainly when parking reaches saturation level, drivers may actually start searching for parking at a substantial distance from their destination, slowing down traffic and causing unsafe traffic situations. However, in the current analysis, we do not include this part of the parking search under the cruising definition.

7.3.3 Cruising for parking

The model driver who *has passed her destination without finding a parking place* is considered to be cruising for parking. During the cruising stage, the driver changes the decision rule shown in Figure 7.3, and is ready to park anywhere as long as it is not *too far from the destination*. We assume that after passing the destination the driver is ready to park at an aerial distance of 100 m or less from it. During cruising, this maximal parking distance grows at a constant rate of 30 m/min until reaching 400 m, when the expansion of the area stops. The turn rule (Figure 7.2) at this stage is updated in order to account for the growth of the appropriate parking area: at each junction, only turns for which the next junction is within the (growing) parking area are considered.

We also assume that each driver has a maximal cruising time, after which she will park her car at an off-street parking facility against a fee, and, in this paper, we set this time equal to 10 minutes for all drivers.

We characterize parking search and cruising at a system level by the following indicators: the fraction of cars who find a parking place on the way to destination; the distribution of cruising time (the time spent searching for parking after failing to park on the way to destination by the drivers who succeeded to park); the average cruising time for drivers that parked during cruising; the fraction of cars that did not find a parking place within the maximal search time of 10 minutes; and the fraction of cars that did not find a parking place within $1/4^{th}$, $1/2^{nd}$ and $3/4^{th}$ of this time, i.e. 2.5, 5, and 7.5 minutes.

7.3.4 Algorithm of car following

The simulation runs at a time resolution of one second. Each time-step, the driving car can advance one or more road cells ahead, pass the junction while deciding on the turn, or occupy a free parking cell. We employ sequential updating and consider all moving cars in a random order, established anew at every time-step. All roads are considered as one-lane and before advancing, the driver checks if a cell ahead is not occupied by another car. If yes, the driver does not advance during the time step. To represent an advance, let us note that at a speed of 12 km/h the car passes 3.33 m during one second, and this distance is shorter than the length of a parking place, which is 4 m. To relate between the car speed and the length of the parking place, we assume that the driver advances one road cell with probability $p = 3.33/4 = \sim 0.833$, and stays at the current road cell with probability $1 - p = \sim 0.167$.

7.3.5 Technical Characteristics of the Model

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

7.4 A non-spatial (point) model of parking

The goal of this paper is to explore the spatial effects of parking dynamics. In order to assess these effects, we compare PARKAGENT to a theoretical ‘point’ model of parking. The model, first described in Benenson and Martens (2008), describes a non-spatial situation in which drivers are able to immediately assess the situation of all parking spaces and hence know immediately whether a free parking place is available or not. If the number of free parking places is higher than the number of cars searching for parking, then all of them park instantaneously. If there are more searching cars than free parking places, then those who park are selected randomly and “cruising” for parking occurs among the remaining cars. The easiest way to imitate this situation is to assume that the number of cars entering the system is systematically higher than the number of cars leaving the system (i.e. access/egress ratio > 1). In such a case, after a certain time period, all parking places will be occupied and newly entering cars will have to wait until parked cars leave the system and vacate a parking space. We assume that the ability of a driver to occupy a vacated parking place does not depend on the time the driver is searching for parking. This means that the queue system (see e.g. Cohen 1969) we investigate does not work on a standard first-come first-served basis.

The point model is formalized as follows. Let us assume that cars arrive to a specific area at rate $a(t)$ (cars/Δt) in order to find a parking place, and that cars already parked in the area leave at an egress rate $e(t)$ (cars/Δt). Let us also assume that the driver's maximum search time is $n*\Delta t$, and that the driver leaves the area if failing to find a parking place during this time. We ignore the spatial dimensions of the area, that is, the distance between the driver's location and the free parking place, and assume that all parking places are occupied at $t = 0$ and that $a(t) \geq e(t)$.

Let us denote $C(t)$ as the overall number of cars in the system, $N(t, t - k*\Delta t)$ as the number of cars that entered the system at $t - k*\Delta t$ and are still searching for a parking place at t. Let $p(t)$ be the fraction of cars that fail to find a parking place between t and $t + \Delta t$, and $F(t)$ be the number of cars that have already searched for a parking place starting from the moment $t - n*\Delta t$ and thus have to leave the system just after t that is, $F(t) = N(t, t - n*\Delta t)$ 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 system of equations:

$$C(t + \Delta t) = C(t) - F(t) + (a(t) - e(t))* \Delta t$$

$$N(t + \Delta t, t) = a(t)*p(t),$$

$$N(t + \Delta t, t - \Delta t) = N(t, t - \Delta t)*p(t),$$

$$N(t + \Delta t, t - 2\Delta t) = N(t, t - 2*\Delta t)*p(t),$$

$$\ldots$$

$$N(t + \Delta t, t - (n - 1)* \Delta t) = N(t, t - (n - 1)* \Delta t)*p(t) \quad (1)$$

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

Below, we will use this point model as the base line against which we will compare the results of PARKAGENT, for cases with a 100% occupancy rate for on-street parking and an arrival rate equal to, or higher than, the egress rate.

7.5 Cruising for commercial parking

Cruising (or searching) for parking in central city areas is a common phenomenon. Drivers prefer to park close to their destinations and pay as little for parking as possible. Hence, if off-street parking is expensive in comparison to on-street parking, or located far away from the destination, and the supply of on-street parking is insufficient, drivers tend to search for a vacant parking space for a while before deciding to park far from the destination or in a for-pay parking lot or garage.

People with different travel motives may cruise for parking. Typically, three types of cruising drivers are distinguished: commercial parkers, work-related parkers (commuter parkers), and residential parkers. The case of commercial parking, which we are investigating in this paper, refers to parking for travel motives like shopping, leisure, or business. Commercial parking differs in three respects from parking by commuters and local residents. First, commuters and residents are long-term parkers (typically, commuters park for 8 hours during daytime and residents for 10-12 hours overnight), while commercial parkers tend to park for a short period of time (ranging from a few minutes to a few hours). Second, commuters and residents park close to the same destination on a day-to-day basis and usually at the same time (commuters typically during early morning, residents typically at the end of the working day), while commercial parkers tend to visit a central city area on an irregular basis and during different periods of the day (typically starting later in the morning than commuters and lasting till closing time of facilities). Third, a large share of commuters and residents tend to have dedicated, and often free, parking close to their working place, while commercial parkers are dependent on public parking spaces, either on-street or off-street. It may therefore come as no surprise that the majority of the studies on cruising for parking focuses on commercial parking (see e.g. Anderson and de Palma 2004; Arnott and Inci 2006; Shoup 2006). Note, however, that cruising behavior is not limited to commercial parkers but may also occur among commuters and residents (for the latter, see the discussion in Martens and Benenson 2008).

Here, we explore the case of commercial parking. As mentioned in Section 2, cruising for commercial parking has not yet been modeled explicitly for the case in which a driver is aware of the parking availability along her search path only. In order to be able to assess the effects of space, we study in details an abstract situation, which, however, is sufficient to reflect the main phenomenon. In the analysis, we assume that drivers travel to a central city area in order to do shopping, visit a café, or for a business meeting, and want to park for a short period of time, up to an hour. We assume that on-street parking is for free, and drivers try to avoid for-pay off-street parking facilities in the area. Hence, drivers will have a tendency to cruise to find a vacant on-street parking place. We assume that all drivers behave in the same way (i.e. no driver heterogeneity) and are willing to search for a maximum amount of time to find an on-street parking place. In case they fail, drivers refer to an off-street parking facility in the area, which is assumed to be immediately available (as in the case of Shoup 2006). We further assume that the drivers' destinations are spread evenly over a rather large central city area covered by a square two-way street network (Figure 7.1b). Drivers' parking search and choice behavior is guided by relatively simple rules, as described in Section 3. As mentioned above, we compare the outcomes of PARKAGENT to the results obtained in the 'point' model.

We analyze parking dynamics for an area with a parking capacity **K** of 7,000 parking places (**K** = 7,000), which is sufficient to ignore boundary effects and corresponds to an area of about 1.5 km^2 within the center of Tel Aviv. We run each scenario for one or two hours, depending on the scenario. In case of a two-hour run, the first hour is used to establish a stable model regime and the second for observing the model dynamics. One-hour runs are performed in cases when the period of initial convergence to a stable regime is unnecessary. The results of the model analysis are presented by several parameters:

- $\mathbf{P_0}$, which represents the fraction of cars that succeeded to park without cruising, i.e. before reaching the destination, as a share of the total number of cars that arrived into the modeled area during the scenario period;
- $\mathbf{T_{cruising}}$, which represents the average search time for the cars that found a parking place while cruising;
- $\mathbf{P_t}$, which represents the share of cars that search for more than t seconds. We present $\mathbf{P_{300}}$, and $\mathbf{P_{600}}$, i.e. the percentage of cars which search for more than 5 and 10 minutes, respectively. Note that $\mathbf{P_{600}}$ represents the percentage of cars arriving during the scenario period but failing to find a parking place during the maximum possible search time (termed 'parking failure' below).

We present the results of two explorations: an analysis of the so-called cruising threshold and an analysis of the differences between the point and spatial model of parking. Let us note that at least some of the results presented below of the spatial modeling can be obtained theoretically; here we present the simulation results.

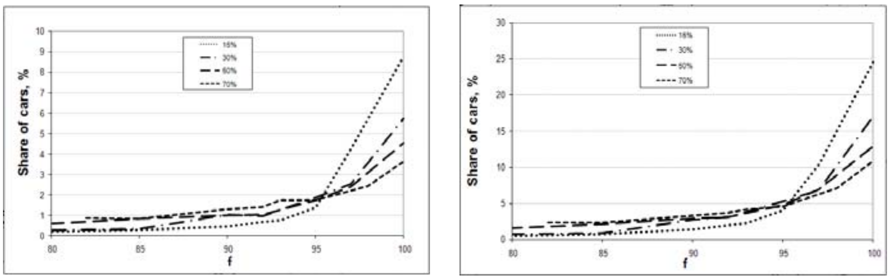
7.6 Cruising threshold

Traffic engineers usually recommend that about 15% of all on-street parking places – one space in every seven – should remain vacant to ensure easy ingress and egress (in Shoup 2005, p. 297). In line with this recommendation, Shoup (Shoup 2006) provides an excellent analysis of the cruising phenomenon and claims that cruising can be eliminated if prices for on-street parking are set in such a way that only 85% of all on-street parking spaces are occupied (see Shoup 2005, Chapter 12-13). Let us call the occupancy rate that results in close-to-zero cruising for parking the 'cruising threshold' $\mathbf{f_{cruising}}$ and explore what is its value.

To obtain an estimate of $\mathbf{f_{cruising}}$, we assume that the arrival and egress rates of cars in the study area, **a** and **e**, are constant in time and equal, i.e. $\mathbf{a(t) = a = e(t) = e}$. For convenience, we will consider **a** and **e** as per hour rates.

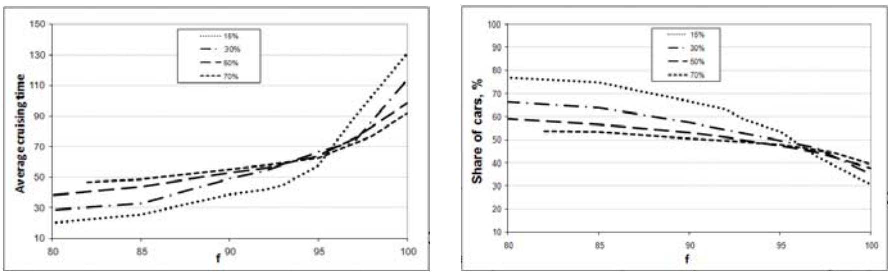
To estimate $\mathbf{f_{cruising}}$ and its possible dependence on **a**, we consider a number of scenarios that differ in terms of (1) the initial occupancy rate, defined as fraction **f** of the occupied parking places in the area , and (2) the number of cars that enter and leave the area (**a** and **e**). We assume uniform distribution of car departures (egress) and car arrivals and investigate cases of low, average and high turnover rates: **a** = **e** = 1,000 cars/hour, **a** = **e** = 2,000 cars/hour, **a** = **e** = 3,500 cars/hour and **a** = **e** = 5,000 cars/hour, i.e. average turnover rates close to 15%, 30%, 50%, and 70%. We search for the cruising threshold $\mathbf{f_{cruising}}$ by varying initial percentages of occupied parking places **f**, increasing it stepwise from 80% to 100%.

Figures 7.4 and 7.5 show the relationship between the share of cars parking without cruising $\mathbf{P_0}$, the average search time $\mathbf{T_{cruising}}$ for cars that find a parking place after cruising, and the percentage of cars searching for parking longer than a given time, for each of the four parking turnover levels defined above.



(a) (b)

Fig. 7.4 Share of cars that search for parking longer than (a) 600 seconds ($\mathbf{P_{600}}$) and (b) 300 seconds ($\mathbf{P_{300}}$), for average turnover rates of 15%, 30%, 50%, and 70%.



(a) (b)

Fig. 7.5 (a) Average cruising time ($\mathbf{T_{cruising}}$) in seconds; and (b) Share of cars parking without cruising (P_0) for average turnover rates of 15%, 30%, 50%, and 70%.

According to Figures 7.4 and 7.5, and comparing the results to the initial view of Shoup, the notion of the cruising threshold $\mathbf{f_{cruising}}$ should be further specified, as the results essentially depend on the turnover rate. For a 15% turnover rate, the model outputs essentially depend in a non-linear way on the parking occupancy rate **f**. For **f** up to 90%, the fraction $\mathbf{P_{600}}$ of cars that fail to find a parking place within 10 minutes remains below 0.5% (Figure 7.4a), $\mathbf{T_{cruising}}$ remains below 40 seconds (Figure 7.5a), and $\mathbf{P_{300}} < 1.5\%$ (Figure 7.4b). For $\mathbf{f} > 90\%$ all these figures quickly grow with the increase in **f,** but yet for **f** = 95%, $\mathbf{T_{cruising}}$ remains below 1 minute and $\mathbf{P_{600}}$ below 3%, i.e. one parking failure per hour. That is, for the relatively low turnover rate, $\mathbf{f_{cruising}}$ should be set at 90% at least, which is essentially higher than the figure proposed by traffic engineers and strongly advocated by Shoup.

For higher turnover rates, the dependencies of the model outputs on **f** are very close to linear up to **f** ~ 95%. To preserve $\mathbf{P_{600}} < 0.5\%$, $\mathbf{T_{cruising}} < 40$ seconds and $\mathbf{P_{300}} < 1.5\%$, which is characteristic of $\mathbf{f_{cruising}}$ for the turnover rate of 15%, $\mathbf{f_{cruising}}$ should be set below 80%, substantially *lower* than 85% as advocated by Shoup. Note that for high turnover levels, even for $\mathbf{f_{cruising}}$, some drivers will be searching for a parking place longer than 10 minutes.

7.7 Effects of space on cruising

The goal of the second series of model runs is to explore and estimate the effect of space on parking search dynamics. Note that spatial effects become insignificant when large numbers of cars are searching for a free parking place. In that case, a cruising car is highly likely to immediately see and occupy a parking place when it is vacated by another driver, just as it happens in the point model. These conditions become realistic if the instantaneous number of cruising cars (1) is high enough to have a car searching for parking in close proximity to *every* parking place, and (2) is essentially higher than the instantaneous number of free parking places.

To quantitatively estimate the effects of space, we consider two series of runs, both for the situation when all parking places are initially occupied (**f** = 100%). The first series investigates the boundary case in which arrival/egress rates remain equal. This case results in zero cruising time in a point model and we compare it to the PARKAGENT results for a range of values of **a** = **e,** starting from 700 cars per hour (i.e. turnover rate **a/K** = 10% per hour), both increasing stepwise by 700 till reaching a level of 7,000 (i.e. turnover rate **a/K** = 100% per hour).

The second series investigates the case of more arrivals than egresses, **a** > **e**. Both in the PARKAGENT and point models there are now *many* arriving cars which compete for a limited number of free parking places. Assuming a 100% initial occupancy rate, we investigate the differences between the outcomes of the spatial and point model for **e** = 1,000 and e = 5,000 cars per hour, while **a** increases stepwise, starting from **e**, while **e** itself remains constant. The case of **a** > **e** demands time to stabilize, and we add a 30 minute period of initial stabilization (i.e. a period three times longer than the maximal search time) before recording the model outcomes.

7.7.1 Equal arrival and egress rates

Figures 7.6 and 7.7 show the dependence of the percentages of cars searching for parking longer than a specified time, the share of cars parking without cruising (**P_0**), the average search time for cars that find a parking place after cruising (**$T_{cruising}$**), and the share of cars which are in search more than 150, 300, and 600 seconds **P_{150}**, **P_{300}**, and **P_{600}**.

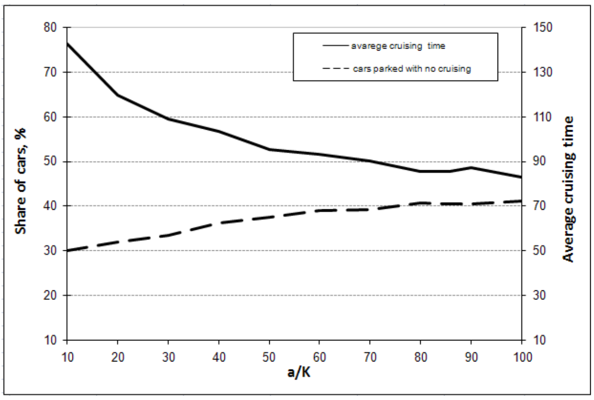


Fig. 7.6 Share of cars parking without cruising (**P_0**) and average cruising time in seconds (**$T_{cruising}$**) as dependent on the average turnover rate.

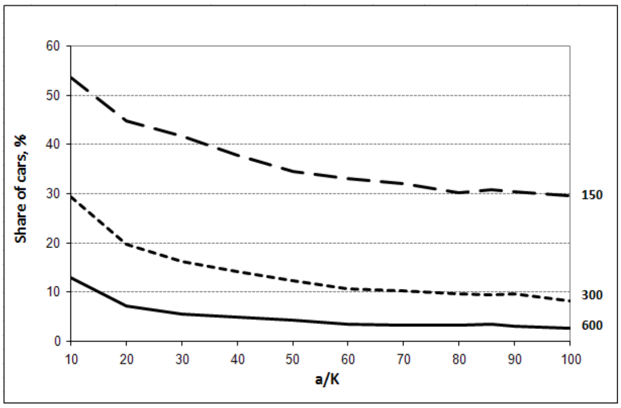


Fig. 7.7 Share of cars that search for more than 150, 300, and 600 seconds before finding a parking place (**P_{150}**, **P_{300}** and **P_{600}**)

The results presented in Figures 7.6 and 7.7 confirm the necessity of a spatial view when constructing a model of parking and cruising. Remember that in a point model of this scenario, all cars find a parking place immediately after entering the system, i.e. average search time is zero, there are no free parking places, and none of the cars is searching. The spatial model demonstrates that this is never so in the real-world, and stresses the importance of the turnover rate. Low turnover rates of 10-20% result in a less than 35% chance to park on the way to the destination and a more than 2-minute average cruising time as a result (Figure 7.6). The chance of parking failure is close to 10%, while about 25% of all cars search for parking for more than 5 minutes (Figure 7.7).

A high turnover rate (90% - 100%) is better for the driver: the chance to park on the way to the destination increases, average cruising time goes down, and the chance of parking failure decreases to less than 5%. However, even for a 100% turnover rate, the estimates of all the parameters are significantly far from "zeros", as characteristic of the point model.

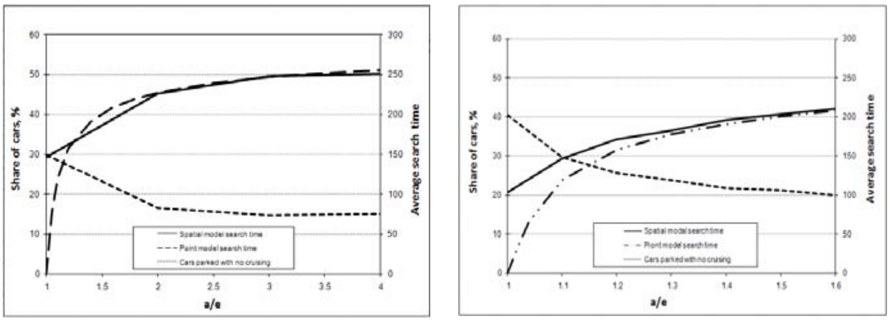
7.7.2 When the point approximation becomes sufficient?

The goal of the third series of model runs is to verify qualitatively the outcomes of the PARKAGENT and point models in case **a** > **e**, when searching cars accumulate and the conditions of "close to point" dynamics become realistic for the spatial model.

The runs of the first series of this kind start with an initial occupancy rate of 100% and **a** = **e** = 1,000 cars/hour (implying a 15% turnover rate). Then we increase **a** by 500 cars/hour, going up to **a** = 4,000 cars/hour. The runs of the second series starts with **a** = **e** = 5,000 (implying a 70% turnover rate) and **a** goes up by 500 to **a** = 8,000. Note, that under these circumstances the turnover rate is determined by the egress rate and remains 15% in the first series and 70% in the second series of runs. Note also, that in these runs we compare the *search time* obtained in the point model to the entire search time $\mathbf{T_{search}}$ in the PARKAGENT model. The search time elapses from the moment the car enters the model environment (and not, as the cruising time, from the moment the car passes the destination) and includes driving towards the destination.

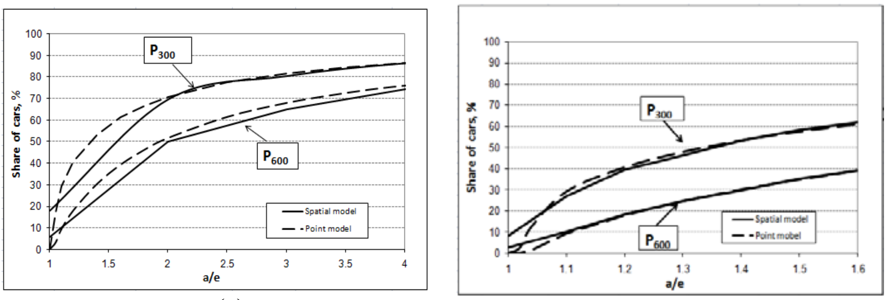
Figures 7.8 and 7.9 present the standard output of the PARKAGENT model together with the estimates obtained with the point model.

As should be expected and can be seen in Figures 7.8 and 7.9, average search time, the number of cruising cars and the chance of failure are higher in PARKAGENT than in the point model. However, the differences between both models become insignificant when the arrival rate exceeds the egress rate by ~10% (i.e. a/e > 1.10).



(a) (b)

Fig. 7.8 Share of cars parking without cruising (**P_0**) and average search time (**T_{search}**): (a) **e** = 1,000 cars/hour, **a** = 1,000 ÷ 4000 cars/hour, (b) **e** = 5,000, **a** = 5,000 ÷ 8,000 cars/hour.



(a) (b)

Fig. 7.9 Share of cars that search for parking longer than 300 and 600 seconds (**P_{300}** and **P_{600}**): (a) **e** = 1000 cars/hour, **a** = 1000 ÷ 4000 cars/hour, (b) **e** = 5,000, **a** = 5000 ÷ 8000 cars/hour.

7.8 Conclusions

Despite the fact that we are only in the beginning of exploring the cruising for parking phenomenon, several preliminary conclusions can already be drawn.

First, the findings so far show that for low levels of parking turnover (at around 15% per hour), the cruising threshold (i.e. parking occupancy level) can be increased from the value of 85%, as advocated by Shoup, to about 90% or even 95%. However, for high levels of parking turnover (more than 50% per hour) the notion of cruising threshold does not work. Under such circumstances, the average cruising time and the share of long searchers (more than 300 seconds) increases almost linearly to the increase in the occupancy level. Even for a parking occupancy level of 80%, the majority of drivers have to cruise in order to find a free parking place and some of the drivers will fail to find a parking place within 10 minutes of search time. This suggests that policy makers, especially those responsible for parking areas with high levels of parking turnover, will be faced with a policy dilemma. Either, they have to be moderate in terms of parking fees and accept high occupancy rates and the related cruising for parking among a substantial share of drivers. Or they will have to set relatively high prices for on-street parking to force parkers to off-street parking facilities, so that the average occupancy rate will fall well below 80% and cruising is largely avoided. The former option will inevitably lead to complaints from drivers about a lack of parking places. The latter option, however, would lead to complaints about overpricing of on-street parking places. After all, in this case, more than 2 out of 10 parking places will be free on average, which makes it practically impossible for policy makers to make a case for high parking fees.

Second, the explorations presented in the paper suggest that spatial effects are unimportant for understanding the cruising phenomenon in a situation when the ratio between arrival and egress rates is above ~1.1. This may occur, for instance, in cases of major events like a soccer game or a rock concert, or, more commonly, in the evening hours in high density cities when residents search for overnight parking (as discussed in Benenson et al. 2008). When such a high (temporary) shortage of on-street parking occurs, many cars are continuously searching for parking in an area, and, consequently, will virtually always occupy a parking place directly after it is being vacated. This happens when the arrival rate is essentially higher than the egress rate and does not depend on the level of parking turnover. In other words, in such circumstances, parking search may be described with a simple mathematical model.

The question remains which of these findings hold true in the real-world, when parking space is heterogeneous (e.g. when parking fees differ between streets or streets differ in terms of parking permissions), destinations are not uniformly distributed over space (e.g. attractions are strongly clustered within a larger area or off-street parking facilities are scarce), and drivers behave heterogeneously (e.g. differ in terms of their willingness to search for on-street parking). It seems likely that an explicit spatial view of parking is necessary in these cases, even under the circumstances of a strong (temporary) imbalance between demand and supply for on-street parking facilities and high parking turnover levels.

The PARKAGENT model is not only a suitable tool to explore these theoretical issues, but can also support decision-makers to set policies that reduce cruising for parking as much as possible.

References

Anderson, S. P. & de Palma, A. (2004). The economics of pricing parking. *Journal of Urban Economics*, 55(1), 1-20

Arnott, R. (2006). Spatial competition between parking garages and downtown parking policy. *Transport Policy - Special Issue on Parking*, 13(6), 458-469

Arnott, R.& Inci, E. (2006). An integrated model of downtown parking and traffic congestion. *Journal of Urban Economics*, 60(3), 418-442

Arnott, R. & Rowse, J. (1999). Modeling parking. *Journal of Urban Economics*, 45(1), 97-124

Benenson, I. and Martens, K. (2008). From modeling parking search to establishing urban parking policy. *Zeitschrift Künstliche Intelligenz*, 08(3), 8-13

Benenson, I., Martens, K. & Birfir, S. (2008). PARKAGENT: An agent-based model of parking in the city. *Computers, Environment and Urban Systems*, 32(6), 431-439

Calthrop, E. & Proost, S. (2006). Regulating on-street parking. *Regional Science and Urban Economics*, 36, 29-48

Carrese, S., Negrenti, A. & Belles, B.B. (2004). Simulation of the parking phase for urban traffic emission models. *TRISTAN V - Triennial Symposium on Transportation Analysis*. Guadeloupe

Cohen, J.W. (1969). *The single server queue*. (Amsterdam: North-Holland)

D'Acierno, L., Gallo, M. & Montella, B. (2006). Optimisation models for the urban parking pricing problem. *Transport Policy*, 13(1), 34-48

Harris, J.M. & Dessouky, Y. (1997). A simulation approach for analyzing parking space availability at a major university. *Proceedings of the 1997 Winter Simulation Conference*

Martens, K. & Benenson, I. (2008). Evaluating urban parking policies with agent-based model of driver parking behavior. *Transportation Research Record: Journal of the Transportation Research Board*, 2046, 37-44

Petiot, R. (2004). Parking enforcement and travel demand management. *Transport Policy,* 11(4), 399-411

Saltzman, R.M. (1997). An animated simulation model for analyzing on-street parking issues. *Simulation*, 69(2), 79-90

Shoup, D.C. (2004). The ideal source of local public revenue. *Regional Science and Urban Economics*, 34(6), 753-784

Shoup, D.C. (2005). *The High cost of free parking*. (Chicago: Planners Press)

Shoup, D.C. (2006). Cruising for parking. *Transport Policy - Special Issue on Parking,* 13(6), 479-486

Thompson, R.G. & Richardson, A.J. (1998). A parking search model. *Transportation Research Part A: Policy and Practice*, 32(3), 159-170

Verhoef, E. T., Nijkamp, P. & Rietveld, P. (1995). The economics of regulatory parking policies: the (im)possibilities of parking policies in traffic regulation. *Transportation Research Part A: General*, 29(2), 141-156

Wang, J. Y. T., Yang, H. & Lindsey, R. (2004). Locating and pricing park-and-ride facilities in a linear monocentric city with deterministic mode choice. *Transportation Research Part B: Methodological*, 38(8), 709-731

Young, W. (2000). Modeling parking. (In D.A., Hensher & K.J., Button (Eds), *Handbook of transport modeling*, (pp. 409-420). Amsterdam: Elsevier)

Young, W., Thompson, R. G. & Taylor, M. A. P. (1991). A review of urban car parking models. *Transport Reviews*, 11(1), 63-84

Zhang, X., Huang, H.-J. & Zhang, H. M. (2007). Integrated daily commuting patterns and optimal road tolls and parking fees in a linear city. *Transportation Research Part B: Methodological*, 42(1), 38-56