Evaluating Urban Parking Policies with Agent-Based Model of Driver Parking Behavior

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This paper presents an explicit agent-based model of parking search in a city. In the model, "drivers" drive toward their destination, search for parking, park, remain at the parking place, and leave. The city's infrastructure is represented by a high-resolution geographic information system (GIS) of the street network and parking lots; information is included on traffic directions and permitted turns, on-street parking permissions, and layers of off-street parking places and lots. Destinations are presented by layers of dwellings and public places. Driver agents belong to one of four categories: residents and guests with dwellings as destinations and employees and customers with public places as destinations. Each agent has its own destination, willingness to pay, time of arrival, and duration of stay. In the model, driver agents are "landed" at a distance of approximately 250 m from their destination, that is, close to the area in which drivers start searching for parking. First, a driver estimates the parking situation in the area and then starts to search for a parking place. During the search, a driver agent accounts for the availability of parking places, differences in pricing, and parking enforcement efforts. The model outputs include distributions of (*a*) search time, (*b*) distance between parking place and destination, (*c*) fees paid by the drivers, and (*d*) parking revenues for the proprietor of paid parking places (whether local authority or private operator). The model is implemented as an ArcGIS application and applied to analyze parking dynamics in an inner city neighborhood in Tel Aviv, Israel, during the course of a regular weekday.

Parking policies have a strong impact on the functioning of cities. The introduction of a new parking policy or changes in the existing policy—for example, differentiation of prices, limitations in parking time, or the establishment of prohibited areas—require a careful analysis and evaluation of these impacts in light of policy goals.

What is a good parking policy? The answer depends on the ambitions of politicians and citizens concerning their city, constraints imposed by the urban physical environment, and the demand for parking. The goals of the policy can vary enormously, ranging from guaranteeing optimal accessibility for car users to minimizing car use in the city, from safeguarding optimal traffic flow to limiting nuisance from (legally and illegally) parked cars, and from creating conditions for maximum turnover in shopping areas to providing maximum parking convenience for local citizens. These multidimensional and often contradictory goals vary between cities and within cities and often remain implicit and cannot be combined into a set of predefined criteria.

The goal of this research project is not to propose parking policies, but to develop a tool that enables the systematic analysis of the impacts of various policy scenarios using a set of quantifiable data relevant to policy makers. In the current paper, the tool will be used to assess a parking policy scenario in which additional parking supply is provided to residents in a neighborhood with a parking demand–supply ratio well above one.

Surprisingly, models have played a limited role in the analysis of urban parking policy and practices, with some notable exceptions [e.g., Shiftan and Golani (*1*) and Dell'Orco and Teodorović (*2*)]. Much of the modeling literature is theoretical in nature and has not been applied to real-world situations [e.g., Voith (*3*), Petiot (*4*), and Lam et al. (*5*)]. Much of the policy-oriented work, in turn, hardly makes use of the potential offered by state-of-the-art modeling techniques [see, for instance, Ferguson (*6*) and Marsden (*7*); the city is presently updating its comprehensive plan, maps, and appendices; new drafts are not yet available.)]. Against this background, it is proposed that an agent-based model (*8*) be used to simulate urban parking policy scenarios and analyze their impacts from a user and public policy perspective.

BRIEF REVIEW OF PARKING MODELS

Various types of models have been developed to simulate and analyze drivers' parking behavior in urban settings [for an elaborate review, see Young et al. (*9*) and Young (*10*)]. One side of the pole represents spatially implicit parking models. This includes the first generation of parking models developed from the late 1980s until today, based on studies of drivers' stated preferences [e.g., Shiftan and Golani (*1*) and Axhausen and Polak (*11*)]. These and later models of the kind are static in nature and assess drivers' stated preferences with logit regression to explain and predict drivers' choice of parking type or parking spot. A parallel stream of spatially implicit and aggregate, but dynamic, models is associated mostly with the economic view of parking processes [e.g., Arnott and Rowse (*12*), Arnott (*13*), Shoup (*14*), and Verhoef et al. (*15*)]. These models tend to formulate an empirically testable pair—parking conditions and parking policy—that optimizes parking utilization per se, peak-hour traffic flows, departure time, or other key parameters (*2, 4, 13, 16–19*).

The other type of parking model—of spatially explicit simulations of drivers' parking search and choice behavior—started in the 1990s and is still in its infancy. The first attempts in this direction deal

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with intentionally restricted situations of search and choice within an off-street parking lot (*20*) or several adjacent street segments (*21*). The authors are aware of two full-fledged attempts of a spatially explicit model. The paper of Thompson and Richardson (*22*) considers driver parking search and choice between on-street and off-street alternatives within a small abstract, but realistic, grid network of two-way streets (20 links of about 50 m in length each). Dell'Orco and Teodorović's (*2*) model does not account for relative location of parking facilities (and in this sense is not spatial), but makes an essential step toward specifying drivers' parking behavior by means of a set of fuzzy rules. The model driver chooses between on-street legal, illegal, and off-street parking with low, moderate, or high fees based on distance to the central business district, previous parking experience, and planned duration of parking. Dell'Orco and Teodorović apply the model to the center of the Bari (Italy), and on the basis of data on actual parking facilities, they use the model to establish appropriate parking fees for the modeled area.

Although the spatially implicit 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 models that potentially do provide these opportunities—spatially explicit and disaggregate—are still in their infancy. None of them can be coupled to a real-world urban infrastructure. The model developed in this paper aims to start filling this gap by providing a realistic framework for investigating drivers' parking search and choice behavior in real cities. Although the model is by no means fully developed yet, initial results do show that the agent-based, spatially explicit approach on which it is based enables the development of a model that can be used to analyze and assess a wide variety of parking policy scenarios in real-world settings.

REQUIREMENTS FOR PARKING MODEL

A closer look shows that urban parking policies aim to solve a long list of specific, often policy-related problems, including

- An imbalance between the costs for on-street and off-street parking (including the possibility of free on-street parking), which may lead to an inefficient use of on-street parking and underutilization of off-street parking lots;
- High levels of demand for parking on specific days and during limited hours only, which are difficult to manage with regular parking management strategies;
- Lack of parking spaces for residential on-street parking, which leads to both high levels of illegal parking and low levels of satisfaction among "resident parkers"; and
- Lack of enforcement, which limits the effectiveness of the available parking management tools.

Whatever the proposed measures or solutions, their effectiveness depends on the types of drivers (local residents, commuters, visitors), the area, the time of day, and the day of the week. For instance, the goal of the policy maker may be to supply free or cheap night parking for residents of a specific neighborhood at the expense of night and weekend customers of cafes and restaurants located on a central avenue crossing the neighborhood. However, without further parking limitations, visitors of bars and restaurants would occupy all free parking places in the nearby residential areas in the course of the evening, and residents arriving late at home would be forced to use paid parking lots that were established for the visitors in the first place.

All problems described above are exacerbated when the overall demand for parking exceeds supply. Note that without appropriate pricing, that will nearly always be the case in urban centers in highly motorized societies. The competition for parking places between drivers becomes crucial in this case, and the violations of parking rules by visitors cause synergetic reactions: residents' parking place search takes longer and the places found will be located farther from the resident's apartment, hence influencing parking availability in further outlying areas. Parking enforcement measures that aim at preventing such a spatial expansion of the parking problem may be ineffective or economically infeasible, especially in cases in which illegal parking behavior is infrequent or occurs only on a limited number of days and during a limited number of hours.

The example above clearly illustrates the basic problem of the policy maker: the impacts of new policy measures become highly dependent on local circumstances in cases in which the demand–supply ratio for parking approaches or exceeds one. However, the typical goal of a municipal parking policy will be to guarantee a situation in which there is a balance between demand for and supply of parking, that is, a demand–supply ratio equal to one. Small changes in parking demand or supply (e.g., due to 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 implies that a practically applicable tool for testing policy measures will have to represent the parking situation in a dynamic way and at the spatial and temporal resolution at which these measures will actually be implemented. Only in this way can the actual "on-street" competition between drivers looking for parking and the aforementioned synergetic reactions be accounted for. In other words, a spatially explicit, agent-based dynamic model of parking in the city is needed to analyze and, ultimately, tackle parking problems in current highly motorized societies.

MODEL OF PARKING IN THE CITY

The proposed model aims to help planners and decision makers formulate and compare parking policies and parking management strategies. The model has been built using a geosimulation approach (*8*). This approach directly represents real-world entities as inanimate and animate model objects, which "behave," that is, change their properties and location in space. The inanimate objects directly represent real-world objects—street segments, parking lots, on-street parking places—by means of layers of features of a high-resolution geographic information system (GIS) of urban infrastructure. In the case of the present model, the only animated objects are car drivers, represented by a layer of (moving) points. Drivers' behavioral rules describe all stages of driving: driving toward the area in which the parking search starts, searching for parking, and leaving the study area after parking. However, the model focuses on the parking search. The model enables the formulation of parking constraints and enforcement levels, and its outcomes can be aggregated over the ensembles of individual drivers by areas and time periods according to the specific interests of the policy maker.

The direct link between the modeling of driver behavior, on the one hand, and a high-resolution GIS of roads, houses, sidewalks, traffic signs, and so forth, on the other, enables a direct translation of urban reality into the simulation model.

Nonanimated Objects

To adequately represent the processes of parking in the city, the model is built on four components of the urban GIS, which are available for an increasing number of cities around the world. Each of the components is discussed below.

Road Network

The model employs a topologically correct road network that contains information on street segment centerline, traffic directions, road width, and turn permissions. To this, information is added on parking permissions, fees, and probability and size of parking fines for each on-street parking segment. The average length of a parking place for one car is about 4 m in Tel Aviv, Israel; parking places of 4 m each along a street are thus constructed (see below). To properly visualize driving in the case of two-way traffic, a street segment is duplicated and each copy serves to visualize traffic in one direction (Figure 1).

Destinations

Each driver in the model aims to park as close as possible to the destination. The destinations are associated with the features of three polygon layers—dwellings, public places, and open spaces. In a case in which several destinations of different types are located in one building, the destination point is multiplied. Destination attractiveness for different groups of drivers is estimated on the basis of the number of apartments in a building and the type and size (small, medium, large) of a public place and open space, among other criteria. When the estimates of attractiveness were unavailable (such as for parks or public gardens), field surveys were carried out.

Off-Street Parking Places

Off-street parking places are established on the base of the layer of houses and parking lots, both available in the GIS database of Tel Aviv Municipality. The number of off-street residential private parking places is an attribute of the building (currently city average per apartment, but can be specified in the field survey). Public parking lots are characterized by capacity (available for the majority of lots) and by ownership (municipal versus private ownership). The latter is relevant in the Tel Aviv case because prices differ by ownership, with lower prices for parking lots owned by the municipality. Exact costs of a parking place in different off-street parking lots were specified on the basis of field surveys.

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 m between the places.

On-Street Parking Places

On-street parking places are constructed on the base of the road network. First, "physically existing" parking places are constructed by dividing the street segment centerline into 4-m fragments and constructing a "parking point" in the middle of each 4-m fragment, starting 4 m (one parking place) from each street corner (Figure 1). The attributes of an on-street parking place are parking permission, fees and, when available, the probability of a fine for illegal parking per parking hour.

Animated Driver Agents

The essence of the agents' representation in a geosimulation model is their behavior. In the case of drivers, the complete description of the behavior should include behavior during (*a*) driving toward the destination, (*b*) searching for parking, (*c*) parking, and (*d*) driving out. The focus here is on the second stage; hence, in the model cars enter the system close to the outer boundary of the parking search area, drive toward their preset destination, and start searching for parking when crossing this boundary. In the same way, the car disappears from the system shortly after leaving the parking place.

The model driver belongs to one of two types—resident or employee. Drivers of different types differ in their "typical" destinations, arrival time, and duration of parking. Say, a typical resident's destination is a dwelling, arrival time between 17:00 and 20:00 and egress time between 07:00 and 09:00; whereas a typical employee destination is an office or commercial building, arrival time between 08:00 and 10:00 and egress time between 17:00 and 19:00. The model can also account for variation in parking demand during the day and between days of the week for drivers of each type. The type, arrival time, and parking duration are assigned to each driver agent entering the system according to the predefined distributions.

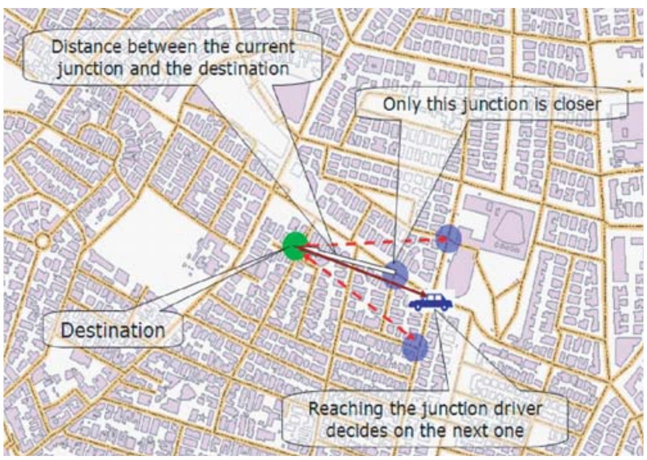
Description of Drivers' Behavior

In what follows it is assumed that the driver agent knows the city and searches for parking near the destination every time when arriving there. This is a typical situation in Tel Aviv, in which most residents do not own a private parking place near their house and park free of charge on the street, and visitors strongly prefer free on-street parking or even illegal parking (given the low chance of being fined) over the high expense of an off-street parking lot. Driving is represented by a sequence of decisions made by the driver: (*a*) at each junction a driver makes a decision about the next segment to drive and (*b*) within the search area a driver makes a recurring decision whether or not to occupy a free parking place. In what follows only residents' parking is considered and it is assumed that all model parameters are identical for all drivers; an investigation has not yet been done on the robustness of the results to the fuzziness in drivers' estimates of parking environment parameters and variability in their behavior.

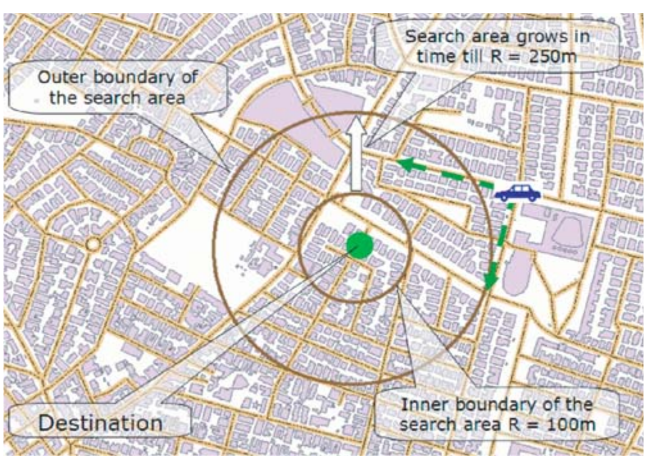
Note that the parameters of drivers' behavioral rules are based on limited field surveys and commonsensical knowledge. More elaborate field surveys are currently being performed, including experiments in which a researcher accompanies a driver searching for parking and records the driver's actions. These and other planned field surveys will generate additional knowledge to more adequately estimate drivers' behavioral rules.

General View of Driver's Way Finding

The choice for a particular segment at a road junction is based on an agent's estimate of the distances between each of the next junctions and the destination. Basically, the driver selects the segment that takes him or her closest to the destination (Figure 2*a*). However, the junction that takes her further can also be chosen in case the former segment was among the set S of segments recently visited (currently S = 4). The latter condition is important to avoid "back and forth" loops in areas with many one-way street segments. This basic algorithm has been tested for various parts of central Tel Aviv, and it demonstrates good correspondence to the authors' own route choice when approaching a final destination as Tel Aviv residents (one actually a former resident).



(a)



(b)

FIGURE 2 Elements of driver's behavior: (*a*) driver's choice of direction and (*b*) growth in search area with time spent searching for a parking place.

Stage 1. Drive Toward Destination, and Estimate the State of On-Street Parking

Driving toward the destination, a driver starts to estimate the fraction of free parking places at a certain air distance D_{EST} from the destination. Yet closer to the destination, at a distance of D_{SRCH}, the driver starts considering actually parking. On the basis of Carrese et al. (*23*), it is assumed that the driving speed at an air distance D_{SRCH} decreases to 12 km/h, no matter what the speed was before. Currently D_{EST} = 250 m and D_{SRCH} = 100 m. It is assumed that, when driving within the (D_{EST}, D_{SRCH}) distance interval, the driver observes every parking place along the driven route and registers the total number N_{ALL} and the number N_{FREE} of free parking places. Reaching D_{SRCH}, the driver estimates the fraction of free among observed parking places $f_{FREE} = N_{FREE}/N_{ALL}$, and enters the area of parking with the expectation of a total of $F_{EXP} = f_{FREE} * D_{SRCH}/4$ free parking places on the remaining route of D_{SRCH} air length until the destination.

Stage 2a. Drive Toward Destination, and Park If Possible

Driving toward the destination within the (D_{SRCH}, 0) air distance interval, the driver observes the parking place to the right (and to the left on one-way streets in which parking is possible on both sides of the street) of his or her current location on the road. If the place is free, the driver has to decide whether to park or continue driving toward the destination. The driver's decision to continue driving or park at the distance D from the destination depends on the expected number of free parking places between this position and the destination: $F_{EXP}(D) = f_{FREE}(D) * D/4$, where $f_{FREE}(D)$ is the accumulated estimate of the fraction of free parking places during the parking search. It is assumed that the driver parks with probability one if $F_{EXP}(D)$ is low, continues driving with probability one if $F_{EXP}(D)$ is high, and parks or continues driving with nonzero probabilities in an intermediate case. Formally, it is assumed that the driver will continue driving toward the destination with probability $P(D) = 0$ if $F_{EXP}(D) < F_1$, $P(D) = 1$ if $F_{EXP}(D) > F_2$, and $P(D) = [F_{EXP}(D) - F_1]/(F_2 - F_1)$ otherwise (Figure 3). $F_1 = 1$ and $F_2 = 3$ are employed in the current model.

Stage 2b. Drive and Park After Missing Destination

The model driver who has passed the destination without parking changes the decision rule and is ready to park anywhere as long as it is not too far from the destination. Formally, this behavior is represented by increasing the area in which the model driver is ready to park and assuming that the radius D_{SRCH} of the search area expands over time in this stage of the parking search. Currently, it is assumed that $D_{SRCH}(t)$ = 100 m + 0.25 m * t (in seconds, t is counted from the moment of passing the destination) until reaching D_{EST} = 250 m, when expansion of the radius stops (Figure 2*b*). Note that $D_{SRCH} = D_{EST}$ = 250 m is reached in 10 min.

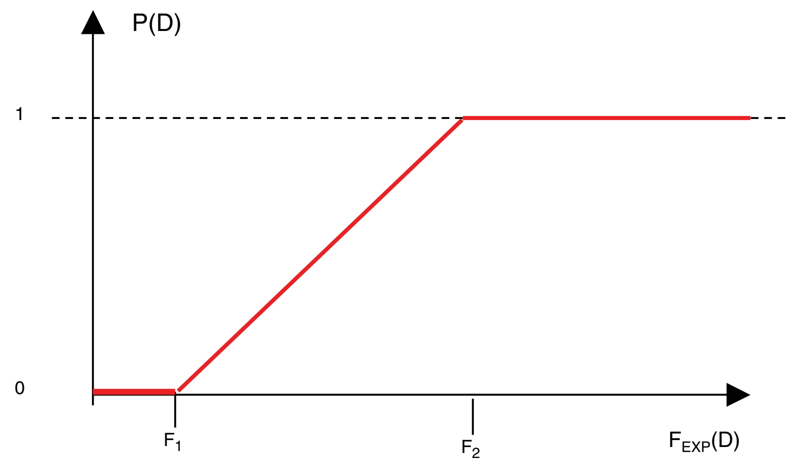


FIGURE 3 Probability to continue driving depends on expected number of free parking places between driver's current location and the destination.

Stage 2c. Drive and Park After Failing for Too Long a Time to Find Parking Place

When failing to find an on-street parking space for a very long time T_{max}, the driver drives to the closest paid parking lot and parks there. $T_{max} = 600$ s = 10 min is used in the current versions of the model.

Stages 3 and 4. Parking Duration and Exiting System

After parking at an on-street parking place or in a parking lot, the model driver remains there during the agent's parking time. Then the driver leaves and disappears from the system.

Technical Characteristics of the Model

The model is implemented as an application developed in the GIS environment. It is based on the *ArcGIS*™ Geographic Information System and C#.NET. The application's performance remains high for thousands of simultaneously parking drivers, which is sufficient for theoretical investigations and practical implementations. Model parameters and results at a resolution of separate cars and parking places are stored in the ArcGIS geodatabase. Policy performance indicators can be estimated for any group of drivers, sets of destinations, and time intervals.

PERFORMANCE INDICATORS

The object-based nature of the model enables following every driver and, thus, direct estimation of the performance of the parking policy from the driver's and the policy maker's point of view.

From the driver's point of view, parking search duration, walking distance, and parking costs are of key importance. Hence, given the set of destinations, time interval, and group of drivers, distributions of the following are estimated:

- Parking search time (Figure 4*a*),
- Distance between parking place and destination (Figure 4*b*), and
- Overall or hourly payment.

From the policy maker's point of view, more indicators are of importance. The policy maker observes (but not necessarily accounts for) drivers' indicators. In addition, the policy maker accounts for the following collective characteristics of the parking situation:

- Fraction of occupied parking places and its change over time;
- Number of cars searching for parking and its changes over time;
- Parking turnover, given as a distribution of parking places by the number of cars that parked there during a specific time interval;
- Revenues from on-street parking; and
- Revenues from paid parking lots, by lots and proprietor.

APPLICATION OF THE MODEL

Given its properties, the model can be applied to compare parking policy scenarios at the level of a center of a (large) city or to assess the consequences of more local changes in the parking situation. The first application of the model has focused on the local level as a way to gain experience with the functions and capabilities of the parking model.

As an example of a local scenario, the construction of a multilevel underground garage is considered, in which all places can be purchased by local residents. This scenario is currently being considered for the Basel neighborhood, a densely built, mixed-use neighborhood located in the old center of Tel Aviv. By allowing the construction of a new parking garage, the municipality aims to ease the parking pressure for residents and reduce the number of complaints about the lack of parking places in the area. To ensure that the goals will be achieved, the municipality wants to make sure that there will be sufficient parking levels and, hence, parking places, in the new garage. 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 demand. He 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 number of apartments in a building and the length of the streets (GIS layers) and accounting for the existing dedicated private parking places, the rough estimate of the residents' demand

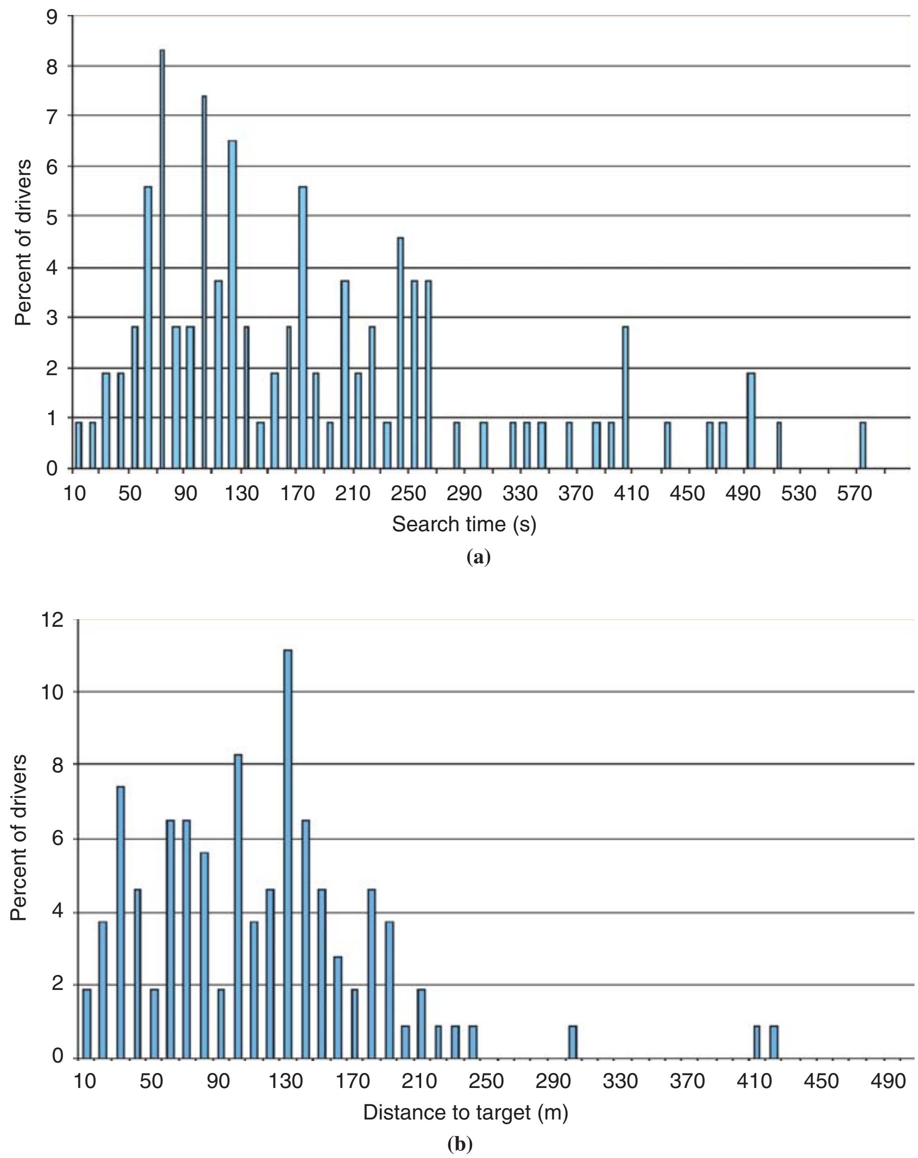


FIGURE 4 Typical model outputs (driver's view): (*a*) distribution of search time and (*b*) distribution of distance between parking place and final destination.

for on-street overnight parking per square kilometer is 8,000 cars, with a supply of about 7,000 places. That is, the demand for overnight parking amounts to about 1.15 cars per parking place. In the field survey it is estimated that about half of the residents remain in the area during working hours. This implies that about 4,000 cars per square kilometer will arrive in the area and search for a parking place at the end of the day.

To estimate the acceptable distance between on-street parking place and the driver's place of residence, the plate numbers of about 800 cars parking in the Basel neighborhood have been recorded during two consecutive nights, and the drivers' addresses have been obtained through the Israeli Central Bureau of Statistics. By combining both data sets, it is estimated that the vast majority of the cars recorded in the survey were parked farther than 250 m air distance (5-min walk) from the drivers' residence. It is thus concluded that, despite the lack of parking space, residents continue their parking search until finding an on-street parking at an acceptable distance from their residence or they decide to park at a paid parking lot in the area.

To investigate the influence of the size of the new garage on the parking situation in the neighborhood, a series of scenarios were studied 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 lay in each of three concentric street blocks around the new lot (Figure 5). The critical period between 17:00 and 20:00 was investigated, when visitors leave and vacate about 50% of the total number of on-street parking places in the neighborhood and about 4,000 residents arrive back home and compete for these vacant places. It was assumed that drivers stop their search and park at a paid lot if failing to find a free-of-charge on-street parking place in 10 min. The rate of search radius growth is 0.25 m/s, and the maximal search radius is thus 250 m.

As could be expected, even 250 additional parking 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 lot can be felt in the central area only (Figure 5; an area with a diameter of about

FIGURE 5 Snapshot of initial model map screen (at 17:00) with two areas around the new parking lot.

330 m), in which the number of on-street parking places is about 1,000 and the demand about 1,200. Despite the fact that the new parking garage decreases the demand–supply ratio in this area to about 1.0, the drivers with destinations outside the central area neutralize the effects. The consequence is that even with the maximal capacity of 250 parking places, the mean search time in the central area decreases only from ~6 to ~5 min, and the average distance between parking place and residence decreases from ~160 to ~130 m. Both improvements are small and will be barely felt by drivers. The characteristics that do change essentially concern the groups of drivers that search for "too long." The strongest decrease occurs in the fraction of residents searching for parking for more than 15 min: the share of this group drops from ~35% in the "no changes" scenario to ~20% in the "250 new parking places" scenario.

On the basis of the model results, it is concluded that the main effect of local improvements in parking supply lies in the reduction of the fraction of drivers who search for a parking place for a long period of time. This finding suggests that assuming no positive feedback loop in regard to increases in car ownership, the additional supply could substantially reduce overall parking search time, at least in the short run. Following the modeling results, if about 250 additional parking places were to be added in the center of each urban block of 500 by 500 m in the dense Tel Aviv center (an addition of about 1,000 parking places every 1 km^2), the share of residents searching for more than 10 min for a parking space would drop to 10% only, with evident consequences for air pollution, traffic congestion, and public opinion. At the same time, even with such additional supply, residents will continue experiencing a lack of parking places in Tel Aviv's central area, that is, they will still face essential average search time and walking distance between parking place and place of residence. This, in turn, suggests that if the developer will be able to offer the parking places in the new garage at a price attractive enough for local residents, they may be eager to buy them. In the case of the Basel neighborhood, where parking demand is essentially higher than supply, the decision about whether the size of the new parking garage should be 150 or 250 places, has thus been reduced to an economic rather than a transport issue (assuming, as noted before, no impact of additional parking supply on car ownership and use, and ignoring local nuisance generated by a parking garage).

CONCLUSIONS AND DISCUSSION

In this paper an agent-based, spatially explicit model of parking in the city was presented. In the model, drivers' parking search behavior is simulated in detail in a high-resolution GIS of a city. The model generates outputs relevant for drivers and policy makers and can thus be used as a tool to compare and evaluate various parking policies. The application of the model to the assessment of a change in a local parking situation has proved satisfactory. It is therefore concluded that the model has substantial potential as a decision-making support tool in the field of urban parking management.

Further research will be necessary to develop this potential. First, the model version presented here is based on a limited number of surveys on drivers' parking behavior. Hence, the behavioral rules are incomplete and suitable only for analyzing the case of free on-street and expensive off-street parking. This has proved sufficient for analyzing the problem of residential parking in central Tel Aviv, but to explore other policy issues and assess alternative parking scenarios, the set of behavioral rules has to be extended. The development of a minimal but sufficient set of rules is a core element of any agent-based model and requires empirical data and extensive testing. An elaborate set of behavioral rules is currently being developed. The behavioral rules, based on a set of field surveys, will make it possible to assess the impacts that the pricing of on-street and off-street parking will have on parking patterns and dynamics.

Second, so far the model has been used only to explore a relatively simple policy question. There are many remaining issues in need of investigation. On a theoretical level, this includes the impact of driver heterogeneity on parking dynamics, as well as the importance of traffic limitations (e.g., one-way streets) and spatial heterogeneity on the emerging patterns of parking (*13*). At the empirical level, the model has to be extended to consider the behavior of many various driver groups simultaneously (e.g., commuters in addition to residents and employees), the impact of enforcement measures on parking behavior, and drivers' learning capacity. 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.

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