Geosimulation of Parking in the City

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ABSTRACT
We present PARKAGENT, an agent-based, spatially explicit, model for parking in the city. PARKAGENT is based on the geosimulation approach, combining real-world GIS database with a multi-agent system. The model simulates the behavior of each driver in a spatially explicit environment and is able to capture the complex self-organizing dynamics of a large collective of parking agents within a non-homogeneous (road) space. The model is developed as an ARCGIS application and can work with a practically unlimited number of drivers. Standard model outputs include distributions of search time, walking distance, and parking costs, each of which can be generated per driver groups, per area and per time interval.

Based on field estimations of supply of and demand for parking and parameters of drivers' behavior, we apply PARKAGENT for investigating several parking scenarios in an over-saturated situation in Tel Aviv. The model shows that, while a limited amount of additional parking has hardly any impact on average search time or walking distance, it strongly affects the occurrence of extreme values. We also compare the effects of a concentrated versus a spatially distributed addition of new parking facilities in a Tel Aviv neighborhood, where demand for parking essentially exceeds supply.

Categories and Subject Descriptors
H.1.0 Information systems, Models and principles, General

General Terms
Algorithms, Measurement, Economics, Experimentation, Human Factors

Keywords
parking, GIS, agent-based modeling, spatially-explicit modeling, on-street parking

1. INTRODUCTION
In this paper we present a geo-simulation model of parking in the city, termed PARKAGENT. The model is developed as a Geographic Automata System [3], and represents urban reality by means of interacting inanimate objects, representing urban infrastructure elements, and animated objects, representing drivers. The model simulates driver's behavior at all stages of the parking process and includes description of driving towards the destination, searching for parking, and exiting the parking place after a variable period of time. Traditional approaches to studying parking in the city aggregate individual drivers into an "average one", who, in turn, reacts to an "average" environment [e.g. 6; 8]. However, averages are inherently conservative and are relatively insensitive to policy interventions. The disaggregate view of parking makes it possible to capture the diversity in terms of driver behavior, urban structure, and transport policies, as well as the dynamic interplay between them. For example, a disaggregate view makes it possible to determine the fraction of unsatisfied drivers – those who either pay too much or search too long for parking, or who park too far from the destination. By using a geosimulation approach, PARKAGENT makes it possible to investigate *spatial and temporal distributions* of payments, search time, distance to destination, etc., which is crucial within the modern city with its highly heterogeneous parking facilities, traffic situation and parking demand.

We are aware of only two models of similar kind [11; 12]. These models, however, focused on simulating the behavior within a constant spatial setting. They neither account for the continuous change in on-street and off-street parking capacity as a result of cars entering and exiting parking facilities, nor for drivers' immediate adaptation to the changing parking situation when driving toward destination.

Our model, in contrast, is able to analyze the instantaneously varying parking situation created by the drivers themselves. We employ it to study residential parking in the evening hours, which has received relatively only limited attention in the literature. In contrast to commuters, who can respond in various ways to changes in parking policies, car-owning residents have little choice when returning home with their cars at the end of the day. In center of most cities in the industrialized world, the majority of them will have to find an on-street parking place, preferably close to the location of residence, for overnight parking. We use the model to analyze how these resident-parkers respond to different parking situations and policies at the home-end of the trip. The case material is taken from the city center of Tel Aviv.

2. GEOSIMULATION AS AUTOMATA-BASED MODELING
Most generally, geosimulation models deal with interacting discrete objects and their behaviors [3]. The methodology of

geosimulation makes use of automata-based techniques, particularly cellular automata for immobile and multi-agent systems for mobile objects. The relationships between the objects are interpreted according to the logic of the entity-relationship model, which considers relationships separately from the objects that are related [2].

Contemporary GIS provides much support for the development of geosimulation models. Each GIS layer can be used to define a class of objects and supply the initial location, form and characteristics of the immobile and mobile objects. GIS can be further employed for storing objects' geographic and attributive properties as they change in time. Non-mapable tables are used for storing and managing relationships of any degree [2].

3. THE PARKAGENT MODEL

The PARKAGENT model has been developed according to the geosimulation principles. It is a *spatially-explicit model*, that is, its dataset contains high-resolution urban GIS, with the layers representing *every inanimate entity of traffic infrastructure important for investigating the parking process* - street segments, on-street parking places, off-street parking places, and buildings (as destinations). Animate objects – drivers – *behave*, i.e. they drive to the destination, search for a parking place, park, and leave the parking place when their activity has ended.

The model is developed as an ArcGIS application, and, despite the very high spatial and temporal resolution, can work with a practically unlimited number of drivers whose destination can be located anywhere in the city. The model interface contains a set of tools for preparing the model database on the base of GIS layers of the city under study, for establishing model scenarios, and for storing the simulation results. The results of the runs can thus be analyzed further.

3.1 The Discrete Representation of Driving and Parking

The focus on the parking process determines the spatial resolution of the model, which, in turn, entails the temporal resolution. The spatial resolution of the model is defined by the typical distance between parking cars **Δd**. The temporal resolution of the model **Δt** is determined by the time it takes a car to pass **Δd** at the typical maximal speed $\mathbf{v_{max}}$ of a car during parking search. The values of **Δd** and $\mathbf{v_{max}}$ in case of Tel-Aviv, as estimated in the field surveys, are: **Δd ≈ 4m**, $\mathbf{v_{max}}$ **< 18 km/h = 5 m/sec.** Consequently, we use $\mathbf{\Delta t = \Delta d/v_{max} \approx 1}$ **sec** as temporal resolution of the model for Tel Aviv case. By using this resolution, we are able to adequately capture the parking search process of drivers and their continuous decisions to park or to continue searching for a parking space.

3.2 The Location of the Animate Objects

Inherent to geosimulation, animate objects are *located by relationship*. That is, the location of a driving car is given by means of linear referencing, while the location of a parked car is given by reference to a parking place. Both driving along a street and occupying and vacating a parking place is represented by means of standard database operations. That is, the advance of a car **c** from location $\mathbf{p_1}$ on segment $\mathbf{s_1}$ to location $\mathbf{p_2}$ on segment $\mathbf{s_2}$, is represented by deleting the row $\mathbf{(c, (s_1, p_1))}$ from the relationship table and inserting the row $\mathbf{(c, (s_2, p_2))}$. It is worth noting that according to the geosimulation paradigm, the cars do not "see" each other; to recognize whether advancement on a street segment is possible, car $\mathbf{c_1}$ has to retrieve its location $\mathbf{(c_1, (s_1, p_1))}$, and then retrieve the location $\mathbf{(s_1, p_2)}$ next to $\mathbf{(s_1, p_1)}$. If the result of this transaction is **NULL**, then $\mathbf{c_1}$ can advance to $\mathbf{(s_1, p_2)}$; otherwise the street segment is jammed and the car can not advance in the current time-step (model iteration).

3.3 The GIS Database

The main components of the model GIS database are (Figure 1):

- street segments (line layer) characterized by driving and parking permissions and prices per segment, turn permissions (non-mapable table of relationships) and junctions (point layer);
- buildings (polygon layer), characterized by type of use and capacity; house entrances (point layer) employed as destination points; and
- off-street parking lots (polygon layer), characterized by capacity and price.

The model tools enable the construction two additional layers. The layer of ***Lanes*** is constructed in order to discretely represent one- and two-way streets. Depending on whether one- or two-way traffic is permitted along a street segment, one or two series of points are constructed, with the points located at a distance of **Δd** from each other. The series of points is either located on a segment centerline (in case of a one-way street) or on two separate lines at both sides of a street centerline (in case of a two-way street). Each series of points is thus used for representing driving in one direction only (Figure 1). The two lines of a two-way street segment touch each other at junctions. The traffic direction along one or two constructed lines is derived from the traffic permission of the segment.

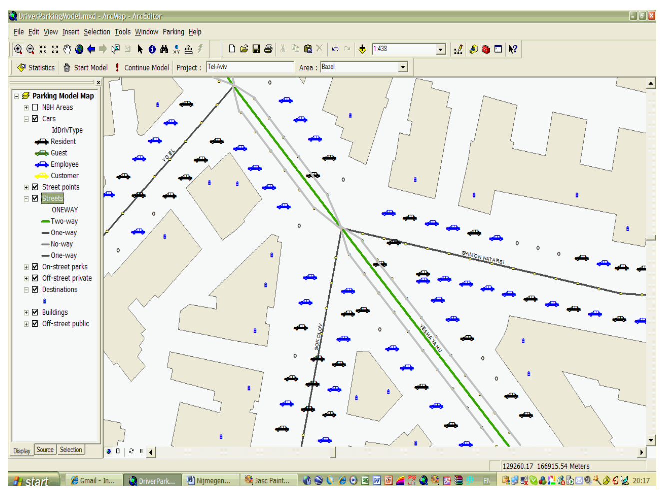

Figure 1. The basic and derived layers of the PARKAGENT model in the ArcGIS model window.

The second additional layer consists of on-street ***parking places***. These are represented by a layer of points always constructed at both sides of the segment centerline. Each parking place is located at a distance of **Δd** from the next parking place (Figure 1). In Tel Aviv this distance **Δd** is about 4 meters and this value is employed in the current version of the model.

The layer of parking places contains all physically existing places for parking, including places where parking is not allowed yet feasible. The actual legal right to park for vehicles of a specific type, for specific time intervals, as well as the price for each group of drivers (including zero price) are either transferred from the road network line features or updated after the layer is constructed. For instance, in case parking is only allowed on one side of a street segment, the parking spots on one side of the center line receive the attribute 'parking not permitted'.

4. DRIVER'S PARKING BEHAVIOUR

The model works in a discrete time and space; at each time-step (iteration) $\mathbf{\Delta t}$ every non-parking vehicle can make a move, the size of which is determined by the vehicle's speed. As mentioned above, the model's temporal resolution is very high: $\mathbf{\Delta t}$ = 1 sec. In case $\mathbf{\Delta d}$ and $\mathbf{\Delta t}$ are changed, all model calculations are automatically adjusted to the new values.

4.1 Representation of Car Advance

Formally, the single car street speed of $\mathbf{v}_{\mathbf{s(treet)}}$ km/h is recalculated into speed $\mathbf{v}_{\mathbf{m(odel)}}$ measured in $\mathbf{\Delta d}$ lengths units per $\mathbf{\Delta t}$. The value of $\mathbf{v}_{\mathbf{m}}$ is then represented as

$$\mathbf{v}_{\mathbf{m}} = \mathbf{v}_{\mathbf{m,int}} + \mathbf{v}_{\mathbf{m,dec}} \quad (1)$$

where $\mathbf{v}_{\mathbf{m,int}}$ is an integer part of $\mathbf{v}_{\mathbf{m}}$ and $\mathbf{v}_{\mathbf{m,dec}}$ is a decimal part.

To illustrate, let $\mathbf{c}$'s speed be 15 km/h, $\mathbf{\Delta d}$ = 4m and $\mathbf{\Delta t}$ = 1 sec. In this case $\mathbf{v}_{\mathbf{m}}$ = 1.04 $\mathbf{\Delta d/\Delta t}$, thus resulting in $\mathbf{v}_{\mathbf{m,int}}$ = 1, $\mathbf{v}_{\mathbf{m,dec}}$ = 0.04.

To simulate driving at a "non-integer" speed $\mathbf{v}_{\mathbf{m}}$, we then generate uniformly distributed on (0, 1) a random number $\mathbf{r}$ and assume that in case there are no cars in front of car $\mathbf{c}$, it advances for $\mathbf{d}_{\mathbf{c}}$ units of $\mathbf{\Delta d}$, where

$$\mathbf{d}_{\mathbf{c}} = \mathbf{v}_{\mathbf{m,int}} + \mathbf{1} \qquad \text{if } \mathbf{v}_{\mathbf{m,dec}} > \mathbf{r}$$

$$\mathbf{d}_{\mathbf{c}} = \mathbf{v}_{\mathbf{m,int}} \qquad \text{otherwise} \quad (2)$$

For example, for a car that drives at 15 km/h, $\mathbf{v}_{\mathbf{m,int}}$ = 1 and $\mathbf{v}_{\mathbf{m,dec}}$ = 0.04 and it advances one $\mathbf{\Delta d}$ = 4m unit deterministically and then one more unit with a probability of 0.04.

During parking search, car velocity is low. As recorded during test trips with drivers, a driver tends to decrease her velocity to 20-25 km/h when starting to estimate the state of parking in an area. The speed is further decreased to 10-12 km/h ($\mathbf{v}_{\mathbf{m,int}}$ = 0 and $\mathbf{v}_{\mathbf{m,dec}}$ ~ 0.69 - 0.83 $\mathbf{\Delta d/\Delta t}$) when a driver actually starts searching for place to park [5] . In the search phase, we thus ignore the possibility of acceleration as employed in e.g. car following models [9]. However, as mentioned above, to account for interaction between parking cars, the model drivers adjust their movements with respect to the car in front of them. Before advancing each $\mathbf{\Delta t}$ distance $\mathbf{d}_{\mathbf{c}}$, the driver checks whether the position in front of her is free or not. If occupied, all further advancements during the given $\mathbf{\Delta t}$ is cancelled.

The order of the cars for advancing is established randomly, anew at every $\mathbf{\Delta t}$.

4.2 Route Choice

A driver located on a street segment advances according to the formulae (1) – (2), accounting for the cars in front of her. When passing a junction, the driver has to decide which direction to take in order to approach towards the destination. In the model, driver's decision is based on the comparison of the distance to the destination from all "next" junctions, which are defined as the first junction on the street segments the driver can choose from for advancement (Figure 2). To avoid looping we assume that the driver does not choose any of two last visited junctions.

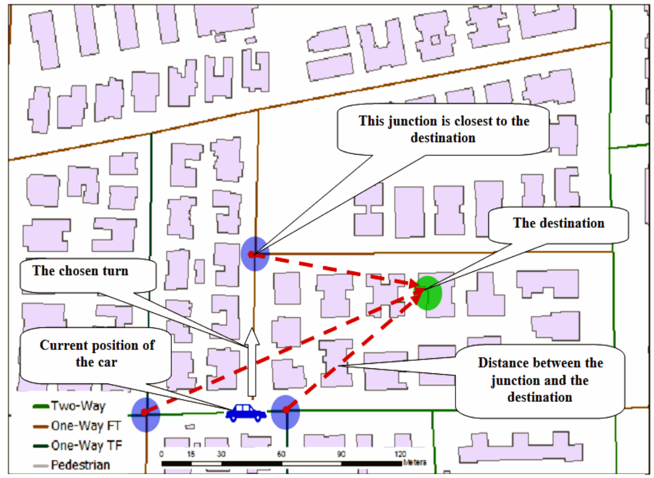

Figure 2. Schematic presentation of the route choice component of driver's behavioral algorithm

We assume that the model driver possesses some knowledge of the city street network and thus selects the segment which next junction is closest to the destination. The model thus follows the approach of [4], who view route choice as the result of a sequence of decisions – one at each intersection encountered.

A driver enters the system at a distance $\mathbf{D}_{\mathbf{awareness}}$ from her destination, where the driver becomes "aware" of the need to start searching for parking. She begins searching for an actual parking place at a distance $\mathbf{D}_{\mathbf{parking}}$. In the current version of the model these distances are set at 300 and 150 meters, respectively, following field observations.

4.3 Representation of Driver's Parking Behaviour

The rules of agent's behavior in the model depend on the stage of the parking process. Generally, approaching the $\mathbf{D}_{\mathbf{awareness}}$ distance the driver follows a sequence of decisions that can be described as follows: (1) Decrease velocity, continue driving and estimate parking supply → (2) Decrease velocity to be able to park and try to park for free as close as possible to the destination → (3) If parking search lasts too long, search for a free place further from the destination or park at an affordable price → (4) If failed, search until finding any parking place, ignoring price or distance. Note that this sequence of decisions holds for Tel Aviv residents returning home, as they can park for free on-street in their own neighborhood. When drivers have to pay for parking, the sequence of decisions will obviously be more complex in nature and depend on parameters like willingness-to-pay for parking and value-of-time of each individual driver.

To formalize this view we introduce the following behavioral components:

1. Driving towards destination, estimating parking supply,
2. Searching for parking and parking before reaching the destination,

3. Searching for parking and parking after passing the destination,
4. Staying at the selected parking place,
5. Leaving the parking place and driving out of the system.

Each of these stages is formalized as follows:

Stage 1: Driving towards destination

From $\mathbf{D_{awareness}}$, a driver estimates the available parking supply by estimating the fraction $\mathbf{p_{unoc}}$:

$$\mathbf{p_{unoc} = N_{unoc}/(N_{unoc} + N_{occ})} \qquad (3)$$

where $\mathbf{N_{occ}}$ is the number of occupied, and $\mathbf{N_{unoc}}$ is the number of unoccupied parking places.

Stage 2: Searching for parking and parking before reaching the destination

At distance $\mathbf{D_{parking}}$ the model driver decreases her velocity to 12 km/h. At any distance $\mathbf{D < D_{parking}}$ she estimates the expected number of free parking places $\mathbf{F_{exp}}$ to be found before reaching the destination as:

$$\mathbf{F_{exp} = p_{unoc} * D/\Delta d} \qquad (4)$$

The driver decides to continue driving with probability $\mathbf{P_{drive}}$, which depends on $\mathbf{F_{exp}}$ in a piecewise-linear manner:

$$\mathbf{P_{drive} = 0} \qquad \mathbf{if\ F_{exp} < F_1}$$

$$\mathbf{P_{drive} = (F_{exp} - F_1)/(F_2 - F_1)} \qquad \mathbf{if\ F_1 \le F_{exp} \le F_2} \qquad (5)$$

$$\mathbf{P_{drive} = 1} \qquad \mathbf{if\ F_2 < F_{exp}}$$

In the model applications the values of $\mathbf{F_1 = 1}$ and $\mathbf{F_2 = 3}$ are used.

To guarantee driver's reaction to the changes in local parking supply as observed during driving, we assume that each driver instantaneously re-estimates parking supply on the way to the destination.

This algorithm results in drivers parking close to the destination in case of a sufficiently high supply of free on-street parking places.

Stage 3: Searching for parking and parking after passing the destination

At this stage, given the fact that on-street parking is for free for residents, the decision to park follows the commonsensical view that "the driver simply tries to find an unoccupied parking place not too far from the destination". We express this in the model by a steady increase of $\mathbf{D_{parking}}$ distance. In what follows we assume that $\mathbf{D_{parking}}$ grows linearly in time at a rate of $\mathbf{\Delta D_{parking}}$, i.e. $\mathbf{D_{parking}(t) = D_{parking} + \Delta D_{parking} * t}$, until reaching the maximal value of $\mathbf{D_{parking,\ max}}$. We also assume that after passing the destination and choosing a street segment at a junction, the driver always tries to stay within or as close as possible to the area with $\mathbf{D_{parking}(t)}$ radius around the destination.

In addition, we assume that the driver whose accumulated search time exceeds $\mathbf{T_{search,max}}$, just parks at the paid parking lot closest to the destination. We follow Tel Aviv reality and assume that an off-street paid parking place is always available.

Stage 4 and 5: Staying at parking place and leaving the system

Each driver parks for the time interval that is attributed exogenously to the driver. After this given parking duration, she drives towards one of the exit points of the system, which is an attribute of the driver as well, following the algorithm (1) – (2). Data on parking duration are derived from field surveys and depend on the type of driver.

4.4 Groups of Drivers

In the model, we distinguish between **Residents** and **Visitors**, who currently differ in terms of the required parking fee and the time they enter and leave the area.

4.5 Model Output

Our model records the life-path of every model driver, based on which a number of aggregate outputs are produced. In this paper we focus on the following aggregate outputs relevant to residents: the *distributions* of parking search time and air distance to destination for the drivers who succeeded to park in the area, the dynamics of the number of free parking places, and the overall number of drivers searching for a parking place longer than 10 minutes. Note, that many other aggregate parameters can be generated, such as the distribution of paid parking fees. All aggregate characteristics are constructed for each group of drivers searching for a parking place in a *specific* area during a *specific* time interval.

The interaction between the basic components of the model could be also analyzed, such as the relationship between the duration of the parking search and the distance between parking place and destination.

5. ESTIMATION OF KEY PARAMETERS

The key parameters of the rules that guide driver's driving, parking search, parking and leaving behavior are based on a number of street surveys carried out in Tel Aviv in 2005-2006. The survey results have furthermore been used for establishing the initial and boundary conditions of the Tel Aviv simulations.

Two main surveys were carried out in the case-study area, the Basel neighborhood in Tel Aviv, during two consecutive weeks. We distinguished between visitors and local residents based on the presence of a local tag on a car (which is supplied by the municipality to local residents only). The total area of the Tel-Aviv center is about 20 km^2. It is divided into nine parking areas of largely equal in size. Only local residents are allowed to park for free on-street within their parking area. The fines for illegal parking in Tel-Aviv are high and the enforcement is tight; in practice, virtually every resident of Tel-Aviv has a local tag. Visitors have to pay parking fees and can park on-street for a maximum of three hours.

In the daytime, the main results of the surveys are as follows:

– Close to 60% of the on-street parking places were occupied by owners of a local area tag.
– Half of the remaining 40% of parking places was occupied by visitors, and half remained empty.

In what follows we employ 60% as an estimate of residents' on-street parking use during daytime.

The main results of the night surveys are as follows:

- All feasible parking places – both legal and illegal – are occupied. The illegal parking is the consequence of the fact, well-known among local residents, that parking enforcement runs only between 6:30 - 21:00h.
- The fraction of visitors recorded in the night survey was close to 10%.
- Based on the plate numbers and data from the Israeli Central Bureau of Statistics we were able to estimate the distribution of the distance between a car's parking place and the driver's destination (home location). More than 50% of the drivers who parked on-street were located at an air distance of less than 100m and more than 90% at an air distance of 250m or less from their home, the latter corresponding to less than 5 min street walk.

Extrapolating the above dependency of the fraction of parked cars on distance to destination, we set $\mathbf{D_{parking,max}}$ = 350 m.

- Based on the local area tags we were able to identify area residents parking at paid parking lots in the neighborhood. Residents entering the lot were asked to estimate their parking search time before entering the lot. The vast majority of residents indicated to be searching either "more than 5 minutes for sure" or "10 minutes or so". This confirms Shoup's [10] view that resident drivers who do not have a dedicated private or public off-street parking place have a tendency to cruise for parking in order to find a free on-street parking place.

Numerically we thus assumed that the typical maximal search time of the residents is $\mathbf{T_{search,max}}$ = 10 minutes and the rate of growth of the area acceptable for parking is $\mathbf{\Delta D_{parking} = (D_{parking,max} - D_{parking})/T_{search,max}}$ = (350 – 150)/10 = 20 m/min.

6. APPLICATION OF THE PARKAGENT MODEL

To explore the potential of the model in practice, it was employed to the analysis of the parking situation in the Basel neighborhood, which is about 1.4 km^2 in size and contains a total of about 1,550 buildings. The Basel neighborhood is suffering from a substantial imbalance between existing parking supply and demand for residential parking. The results of the survey confirm the municipality's view that the problems are most notable in the evening hours, when local residents have problems finding a parking place to park their vehicle overnight. The solution proposed by the municipality is the extension of a planned underground parking garage underneath a yet-to-be-built residential building and sale of the additional parking places to residents living nearby. This new residential building is located in the center of the Basel neighborhood.

The estimate of total parking demand in the Basel area is based on the number of apartments and registered businesses per building, and on the number of parking tags issued to the residents in the area, both available as part of Tel Aviv Municipal GIS. The estimate of on-street parking supply is based on the GIS layer of streets. All physically available spaces in the area are used for overnight parking. The only unoccupied places at night are located at the entrances to public and private off-street parking places, at pedestrian crossings, and next to junctions. All these can be easily estimated from the GIS data. Data on off-street public parking supply were also taken for the GIS data, while off-street private parking space was estimated based on the field surveys.

Based on the estimate of residents' parking demand and the observed 10% visitor parkers, the overall demand/supply ratio overnight is about 3,500/2,850 ≈ 1.23. However, the demand/supply ratio varies during the evening period 17:00-21:00h, during which the share of unoccupied parking places drops from 20% to 0%, the share of visitors parking on-street decreases from the observed 20% to 10%, and residents enter the area to find overnight parking.

6.1 Estimating the Effects of the New Parking Facility

The question is now whether the addition of off-street parking places to the existing parking stock can improve the parking situation of the local residents. Since the additional parking places are sold to local residents, they *de facto* reduce the number of drivers looking for on-street parking, assuming no impact on the motorization rate of local residents.

Given the preference of residents to park as close as possible to home, the impact of the additional parking capacity will not be the same all over the Basel neighborhood. To account for the distance between the new parking facility and drivers' destinations, we defined two concentric polygonal rings around the new parking facility with sizes of about 0.7x0.7 km (inner ring), and the remainder of the 1.4x1.0 km Basel area (outer ring). The effects of the new parking garage are estimated for each area separately. In our simulations, we have assumed that all parking places in the new parking garage are purchased by residents of the inner ring, following the reference of residents to park as close to home as possible.

The simulation encompasses the period 17.00-21.00h, during which visitors leave and residents enter the area. We focused on two performance indicators: (1) the distribution of search time; and (2) the distribution of air distance to destination. Both are calculated separately for the drivers with destinations in the inner ring and the outer ring. We run the model for a number of scenarios, differing in terms of the size N of the additional off-street parking facility. The base scenario (N=0) is compared to five scenarios, with values of N = 50, 100, 150, 200 and 250.

It is intuitively evident that even the maximal possible capacity of the new parking lot – 250 places – cannot have a large effect on the average parking situation in an area where parking supply is about 650 places below demand (3,500 - 2,850 = 650). The model investigation confirms this: even for a 250 places parking lot and for drivers whose destination is within the inner ring, the decrease in average search time and walking distance for on-street parkers is low, especially during the last hour of the investigated period (20:00-21:00h). The decrease in mean search time is about 15% (from 250 to 215 seconds); the decrease in distance to destination is almost insignificant - 10% (from 150 to 135 meters). Obviously, the effects are even smaller in case less additional capacity is provided. In the outer ring the mean search time and distance to destination show hardly any decrease.

That is, a new parking lot will hardly change the average residents' perception of the parking situation in the area as a whole. The reason for the limited impact of the additional parking supply is evident: with the increase in supply within the inner ring, drivers with destination in the outer ring will park more often in the inner one, preserving the high demand/supply ratio there. The only residents experiencing and perceiving a real improvement in their parking situation, are the ones who purchase a parking place in the new garage.

6.2 The Size of a New Parking Lot

The construction of large underground multi-story garages for local residents is a hot issue in the public debate in Tel Aviv. To justify the construction, parking in these garages will be charged for, however, the residents' fees would be low, and they can use the garage on a day-to-day basis when need arises. In order to account for the attractiveness of a garage in the city center for visitors, we assumed that only half of the parking places in such a garage would be available for the residents in the evening. Considering the Basel neighborhood as an example, a 1,000 places garage would be close to supply a parking place to those local residents who currently fail to find a free parking place in the area and have to park at the existing, expensive, paid lots overnight, and for additional visitors who want to stay in the area overnight.

To estimate the quantitative consequences of this parking strategy, we compare two scenarios in which 1,000 off-street parking places are added to the Basel neighborhood. In one scenario the places are added as one large lot, in the other scenario they are distributed between four smaller lots of each 250 parking places located at a distance of about 500 m from each other (Figure 3). Note that the parking arrangement in this scenario is different from the scenario discussed above. In the latter scenario, the additional parking capacity was sold to specific residents who gained a dedicated parking place. In the current experiment, all residents can use the additional parking places against a low fee. Given this arrangement, we assumed that drivers continue searching for free on-street parking until (1) the parking lot closest to the destination is within $\mathbf{D_{parking}(t)}$ distance from the destination and the parking lot is closer to the driver in its current position than the destination, or (2) the maximal search time of 10 minutes is reached.

We compare the two scenarios in terms of the number of "long-searchers", i.e. the number of drivers who fail to find a free on-street parking place or a space in the new parking facility within the maximal search time of 10 minutes (and thus go to the nearest new parking lot). Note that drivers aim to park within walking distance from their home location, i.e. within a radius of 350 meter from their destination. The results show that in case of four parking lots, the number of "long-searchers" – those who do not find a parking place within 10 minutes – varies between 250 and 300 (from about 650 in the current situation). In case one large parking lot is added, the number of long-searchers varies between 400 and 450. This substantial difference is a direct consequence of the revealed tendency to park as close as possible to the final destination (home location). With four parking lots distributed over the neighborhood, it is more likely that the nearest parking lot is at walking distance from the destination and the distance between the parking lot and the home location is *smaller* than the distance between a free on-street parking place and the home location, than in case of one large centralized parking lot. Hence, a smaller share of residents will continue looking for free on-street parking in case additional off-street parking supply is distributed over the neighborhood. That is, despite supplying the same physical place, the problems of cruising, air pollution, and parking rules violations may well remain substantial in case of centralized supply of additional parking in comparison with additional supply distributed over the neighborhood.

Note that this result was obtained while investigating the Basel neighborhood only. The slight (perceived) reduction in parking pressure in the Basel neighborhood may well induce residents of surrounding neighborhoods within the same parking zone to enter the Basel area in search of a free on-street parking space. In that case, the effects of either scenario on the fraction of "long-searchers" may be well lower than the estimates presented here.

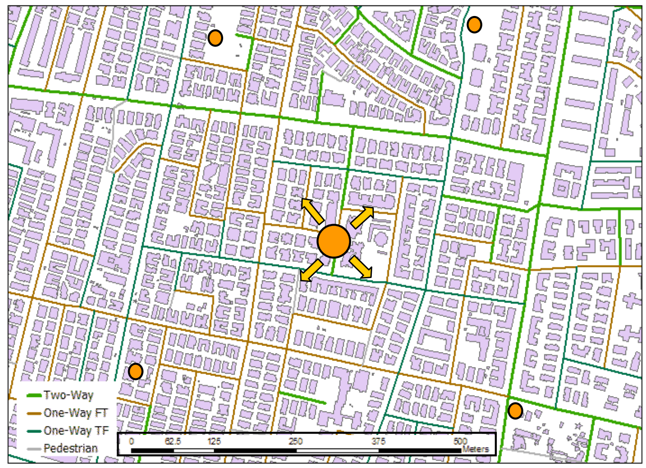

Figure 3. The scenario of one large parking lot of 1,000 places in the center of the neighborhood, versus the scenario of four parking lots of 250 places distributed evenly over the neighborhood.

Being in line with common-sense expectations, the PARKAGENT model thus enables quantifying the impact of different spatial scenarios. As the example suggests, the model could be used to compare various distributions of off-street parking facilities over the city under various conditions and for various user groups and help to determine an optimal solution.

6.3 Reflection on Results

The experimental data and model results presented above demonstrate that the parking pressure as a result of excess demand in the dense areas of central Tel Aviv can be reduced to some extent by adding a network of small parking lots at an appropriate distance between each other. However, this finding should be treated with care. Like in the case of road capacity, more supply may generate more demand for parking. Thus, the improvement in search time and walking distance may be short-term effects. If more residents will purchase cars *because* of the improved parking situation, the long-term effect of additional capacity is actually likely to be negative. Given the high parking pressure and still relatively low level of motorization in central Tel Aviv, it is not unlikely that the small improvement in the parking situation may be enough for the *marginal* resident to purchase a car, or for car-owning rather than carless households to move in.

7. CONCLUSIONS

In this paper, we have presented a spatially-explicit, agent-based, model for parking in the city. Unlike traditionally models, it simulates the behavior of each driver in a spatially explicit environment. Because of this, the model is able to capture the complex dynamics that can occur between large sets of agents, as well as the impacts of non-homogeneous (road) space. As stressed by Arnott [1], current models are neither able to capture this heterogeneity, nor to estimate its possible impacts.

The small case-study presented in the paper provides a window on the possibilities of PARKAGENT. Instead of investigating the changes in average search time as aggregated over space, which might be relatively insensitive to changes in parking policy, the agent-based model easily captures the spatially distributed effects of changes in parking supply. Given the disproportional human reaction to extremes [7], this is a major advantage of spatially explicit models over existing parking models.

PARKAGENT's ability to simulate the complex dynamics of the parking system in detail *and* generate data about the system performance for different groups of drivers is especially important in saturated parking situations. In such situations, with an instantaneous demand/supply ratio essentially varying around one or even substantially exceeding one, averages are unlikely to capture the essential performance of the parking system due to the inherently uncertain nature of the car parking system [11]. Parking management is especially called for in saturated situations, where it is always hard to foresee the effects of interventions. In this situation, high-resolution, spatially explicit, models are able to provide details of the distribution of key parameters like search times and walking distances that result from different policy scenarios.

Given these advantages, geosimulation thus seems to be a promising tool for urban decision-makers. The ultimate goal of the model is to help decision-makers propose, assess, and evaluate spatially adaptive policy measures, including optimal pricing for on-street parking over a heterogeneous city.

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