

Agent-Based Model of Driver Parking Behavior As a Tool for Urban Parking Policy Evaluation

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THE GOAL

Parking policies have a strong impact on the functioning of cities. The introduction of a new or changes in the existing parking policy – e.g. differentiation of prices, limitations in parking time, or the establishment of prohibited areas – requires 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 turn-over in shopping areas to providing maximum parking convenience for local citizens. These multi-dimensional 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 our research is not proposing parking policies, but developing *tools* that enable the systematic analysis of the impacts of various policy scenarios, using a set of quantifiable data deemed important by policy-makers.

Surprisingly, models have played a limited role in the analysis of urban parking policy and practices, with some notable exceptions (e.g. Shiftan 2001). Much of the modeling literature is theoretical in nature and has not been applied to real-world situation (e.g. Voith 1998; Petiot 2004; Lam 2006). Much of the policy-oriented work, in turn, hardly makes use of potential offered by state-of-the-art modeling techniques (e.g. Ferguson 2003; Marsden 2006). Against this background, we propose using an agent-based model (Benenson, Torrens, 2004) to simulate urban parking policy scenarios and analyze their impacts from user and public policy perspective.

PARKING POLICY DEMANDS HIGH RESOLUTION AND SPATIALLY EXPLICIT VIEW OF THE CITY

A closer look shows that urban parking policies aim to solve a long list of specific problems, among which:

- imbalance between the costs for on-street and off-street parking, which leads to an inefficient use of on-street parking and under-utilization of off-street parking lots;
- possibility of free parking within one's own residential district, which limits the possibilities for parking management through pricing;
- lack of parking permits for residential on-street parking, which leads to high levels of illegal parking, over-demand for parking spaces, and low grades of satisfaction among 'resident parkers';
- lack of enforcement, which limits the effectiveness of the – already limited – parking management tools;
- etc.

Whatever the proposed measures or solutions, their effectiveness depends on the type of drivers (local residents, commuters, visitors), the area, the time of day, and day of the week. For instance, the policy maker can aim at supplying free or as cheap as possible night parking for households of a specific residential area 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, and residents arriving late at home would be forced to use paid parking lots that were established for the visitors in the first place.

The competition for parking places between groups of drivers is crucial in case the overall demand for parking exceeds supply. Note that without appropriate pricing, this will nearly always be the case in urban centers in highly motorized societies. The violations of parking rules by visitors, even at a low frequency, causes synergetic reactions – residents' parking place search takes longer and the places found will be located farther from the resident's apartment. Further outlying areas, in turn, will experience a decrease in parking availability. Parking enforcement measures may be ineffective or economically infeasible, especially in case illegal parking behavior is infrequent or only occurs on a limited number of days and hours.

The above example clearly illustrates the problems of the policy maker. In general terms, the problem is that the impacts of new policy measures become highly dependent on local circumstances in all those cases in which the demand/supply ratio approaches or exceeds one. Since cities have implemented policies to approach a situation of a balance between demand for and supply of parking, small changes in parking demand may already cause such situations to occur (e.g. due to increasing car ownership, densification of land uses, or changes in traffic arrangements). The impacts of new parking measures become thus extremely difficult to forecast, without adequate tools that enable testing of policy measures at the spatial and temporal resolution at which these measures will actually be implemented. This requires that the parking situation in an area be represented in a dynamic way, accounting for the actual 'on-street' competition between drivers looking for parking and for the synergetic reactions that can occur between driver groups and areas, as discussed in the example above. In other words, we need a spatially explicit agent-based dynamic model of parking in the city in order to analyze, and ultimately tackle, parking problems in current highly motorized societies.

THE MODEL OF PARKING IN THE CITY

The proposed model aims helping planners and decision-makers to formulate and compare parking policies and parking management. The model has been built using a Geosimulation approach (Benenson, Torrens, 2004). 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 the features that belong to the layers of high-resolution GIS of urban infrastructure. In the case of our model, the only animated objects are car drivers, and their behavioral rules describe all stages of driving: driving towards the area in which parking search starts, parking search, and leaving the study area after parking. However, the model focuses on 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, etc., enables a direct translation of urban reality into the simulation model.

Non-animated objects

To adequately represent the processes of parking in the city, we build on the following components of the urban GIS, which are available for the majority of Israeli cities:

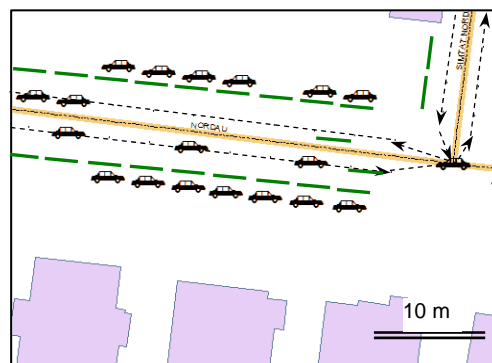
Road network: The model employs a topologically correct road network that contains information on traffic directions, road width, and turn permissions. To this, information is added regarding parking permissions, fees, and probability and size of parking fines, for each on-street parking segment. The road network is employed for representing driving and, accounting for on-street parking permissions, for building and classifying on-street parking places. Typical length of a parking place in Tel-Aviv is 4 meter, and the model works at this resolution. To properly visualize driving in case of two-way traffic, the 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 centroids of the features that belong to one of three polygon layers – *Dwellings*, *Public places*, and *Open spaces*. Destinations differ in type – dwelling, hospital, restaurant, office, park, market place, etc. – which determines the demand for parking places. In case several destinations of different types are located in one building, the destination point is multiplied. We account for variation in parking demand during the day and between days of the week. To fully represent destination attractiveness we employ time-coverages – series of non-overlapping time-intervals that cover 24 hours of the day. Each time interval is characterized by the number of drivers aiming at the destination. For each destination we consider two coverages, characteristic of the working day and the weekend. The temporal resolution of this representation is 15 minutes. A typical example of the time-coverage for a grocery store open from 7:30 till 16:00 with 5 employees and 10 motorized visitors per hour during working hours are $\{[0, 7:15), 0\}$, $\{[7:15, 7:30), 5\}$, $\{[7:30, 16:00), 10\}$, $\{[16:00, 24:00), 0\}$. This sequence is stored in a database table for each destination. Destination attractiveness is estimated based on the number of apartments in the dwelling, or type and size (small, medium, large) attributes of the public place and open space. In situations in which precise estimates of attractiveness are required, field surveys are performed.

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 house (currently city average, but can be specified in the field survey). Public parking lots are characterized by their capacity and per hour price. For both private and public parking lots, every parking place is represented as a point in order to relate between them and the parking cars.

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-meter fragments, and constructing a “parking point” in the middle of each 4-meter fragment 5m from the street edge (Figure 1). The attributes of the on-street parking place are parking permission, fees and, when available, the probability of a fine for illegal parking per parking hour.

Figure 1: To represent two-way traffic street centerline is duplicated, and each copy is employed for representing one direction. Parking places are built by dividing the segments into 4m fragments.



Animated driver agents

The essence of the agents' representation in a Geosimulation model is their behavior. In case of drivers, the complete description of the behavior should include behavior during: (1) driving towards the destination, (2) parking search, (3) parking, and (4) driving out. We focus on the second stage, and the model is thus built in two versions – the “full” one accounts for the entire driving process, beginning from the moment the car enters the system till the moment it leave through one of the exit points. In the “parking only” version, drivers “land” and immediately begin their parking search at the outer boundary of the parking search area, and disappear from the system just after leaving the parking place.

The description of drivers' behavior

In what follows we assume that the driver agent knows the city, but searches for parking near the destination every time when arriving there. This is a typical situation in Tel Aviv, where most residents do not own a parking place near their house and park on-street, and visitors strongly prefer free on-street parking or even illegal parking (given the close-to-zero chance to be fined) over the high expenses of an off-street parking lot. We represent driving by a sequence of decisions made by the driver: (1) at each junction a driver makes a decision regarding the next segment to drive; and (2) within the search area a driver makes a recurring decision whether or not to occupy a free parking place. In what follows we assume that all the model parameters are identical for all drivers; we have not yet investigated the robustness of the results to fuzziness in drivers' estimates of parking environment parameters and variability in their behavior.

Stage 1a – driving towards area of the parking search: The choice of the 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 one of the segments which takes her closer to the destination (Figure 2a); however, the junctions that take her further can be also chosen in case all junctions that take her closer were recently visited. The latter condition is important in the areas with many one-way street segments. We have tested this basic algorithm on the basis of various excerpts of Tel Aviv areas and it demonstrates good correspondence to our own route choice as Tel Aviv residents.

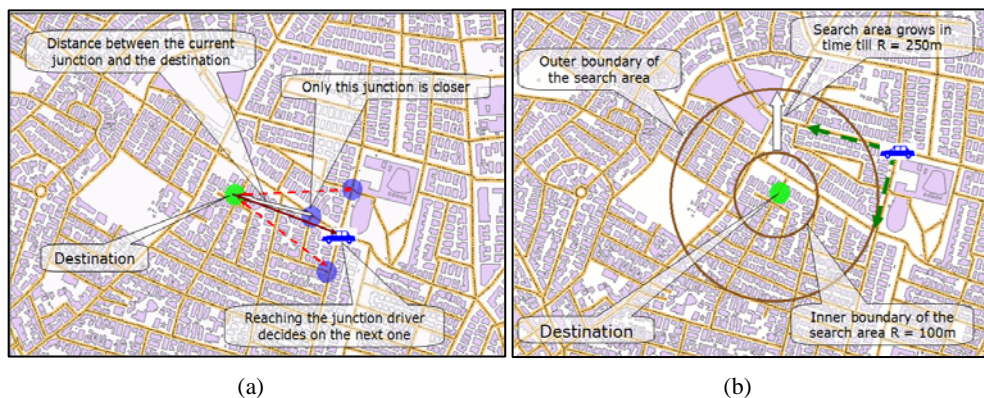


Figure 2. (a) Driver's choice of direction; (b) Grows of the search area with the increase in duration of unsuccessful search.

Stage 1b – drive towards destination and estimate the state of on-street parking: Driving towards the destination, at a certain distance D_{EST} the driver starts to estimate the fraction of free parking places, while yet closer to the destination, at a distance of D_{SRCH} , the driver starts considering to park. Based on Carrese (2004), we assume that the driving speed at a distance D_{SRCH} decreases to

12 km/h, no matter what was the speed before. Currently we set $D_{EST} = 250m$ and $D_{SRCH} = 100m$ (air distance). We assume that, when driving within the (D_{EST}, D_{SRCH}) distance interval, the driver observes N_{FREE} parking places from a total of N_{ALL} . Reaching D_{SRCH} , the driver estimates the fraction of parking places $f_{FREE} = N_{FREE}/N_{ALL}$, and enters the area of parking with the expectation of a total of $F_{EXP} = f_{FREE} * N_{AHEAD}$ free parking places on the remaining route till the destination, where N_{AHEAD} is an expectation of the overall number of parking places on this route.

Stage 2a – drive towards destination and park if possible: Driving towards the destination, the driver decides to park or not based on her expectation of F_{EXP} – the expected number free parking places between the current position and the destination. Let us denote as D the (air) distance between the driver and the destination. The driver decides to drive further based on $F_{EXP}(D) = f_{FREE} * N_{AHEAD}(D)$. If $F_{EXP}(D) < F_1$ then the driver will park. If $F_{EXP}(D) \geq F_1$ then the driver will continue driving towards the destination with probability $P(D) = \min\{1, (F_{EXP}(D) - F_1)/(F_2 - F_1)\}$ (Figure 3). When driving, the driver instantaneously re-estimates f_{FREE} , $N_{AHEAD}(D)$ and $F_{EXP}(D)$. We employ $F_1 = 1$, $F_2 = 3$ in the current model.

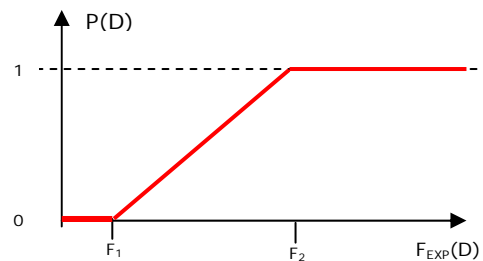


Figure 3: Probability to continue driving depending on the expected number of free parking places between current location on the road and the destination.

Stage 2b – drive and park after failing to find parking place for a long time or missing destination: The model driver who fails to park for a sufficiently long time $T_{miss} = 120$ seconds or has passed her destination without parking, changes the decision rule, and is ready to park anywhere as long as it is not too far from the destination. Formally, we represent this behavior by increasing the area the model driver is ready to park within and assume that the radius D_{SRCH} of the search area begins to expand in time in this stage of the parking search. Currently, we assume that $D_{SRCH}(t) = 100m + 0.25m * t$ (in seconds) until reaching $D_{EST} = 250m$ when the growth cancels. t is counted from T_{miss} or from the moment of passing the destination. Note that $D_{SRCH} = D_{EST} = 250m$ is reached in 10 minutes.

Stage 2c – drive and park after failing to find parking place for too long time: When failing to find on-street parking for a very long time T_{max} , the driver drives to the closest paid parking lot and parks there. We use $T_{max} = 600$ seconds in the current version of the model.

Stages 3 and 4: After parking at an on-street parking place or in parking lot, the model driver remains there for a given time (agent's property). Then she leaves and drives towards the pre-defined exit point of the system according to the algorithm of Stage 1a.

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:

Drivers' view: Given the set of targets, time interval, and group of drivers we estimate distributions of:

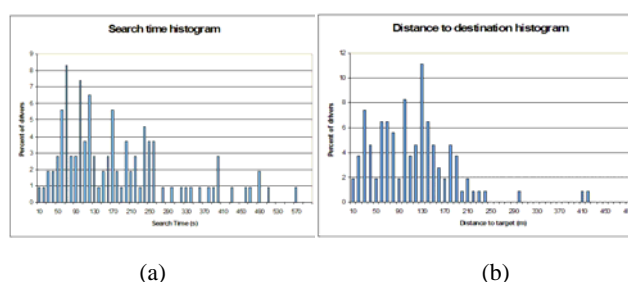
- Parking search time (Figure 4a)

- Distance between parking place and destination (Figure 4b)
- Overall/hourly payment

Policy-maker's view: 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 changes in time
- Number of cars searching for parking place, and its changes in time
- Turnover, given as a distribution of parking places by the number of cars that parked there
- Revenues from on-street parking
- Revenues from paid parking lots, by lots and proprietor

Figure 4: Part of the typical model output (driver's view).



Technical characteristics of the model

The model is implemented as a VB ArcGIS application and can work with practically unlimited number of simultaneously parking drivers. Model parameters and results at resolution of cars and parking places are managed with the SQL Server 2000 and, thus, policy performance indicators can be constructed for various groups of drivers, sets of targets and time sub-intervals without re-running the simulation.

APPLICATION OF THE MODEL

We are currently investigating and comparing several parking policy scenarios for the central area of Tel Aviv, as well as exploring the consequences of more local changes in the parking situation. The outcomes of these explorations will be reported at the conference.

Each of the policy scenarios gives a different answer to the pressing parking problems experienced in the central area of Tel Aviv. This area covers approximately 20 km². It is a densely built-up area characterized by a mix of land uses, including offices, shops, bars, restaurants, and other leisure activities. Most residential buildings are three to eight storey high and often provide none or only limited amount of private parking. Motorization levels in Tel Aviv have been increasing over the past two decades, and on-street residential parking has become the norm in the central area. Employment and leisure activities are scattered throughout the area, with a concentration in a limited number of centers and on traditional main streets. Off-street parking facilities are limited in number, are often small, and expensive in comparison to on-street parking. On-street parking in the area is free for residents living in the area, while visitors pay a very low fee. Parking enforcement is low in most areas and fines for illegal parking are relatively low, with the exception of illegal parking on pavements. The result is a high pressure on parking places, an under-utilization of off-street parking lots throughout most of the day and week, and high levels of illegal parking, obstructing pedestrian, car and bus traffic and creating dangerous traffic situations.

Within the framework of the project, various policy scenarios will be tested to improve the existing parking situation. For now, three scenarios have been distinguished.

Resident-friendly scenario: Goal of this scenario is to improve the parking turnover along main streets in order to improve the car accessibility of shops, bars, restaurants, etc. located along the main streets, *without* infringing on the current 'parking rights' of Tel Aviv residents. Two tools to increase turnover can be distinguished: pricing and/or time limitations. In the first case, the price for on-street parking on the main streets is increased, while prices for off-street parking and parking along side streets remains the same. In the second case, only a limitation is set regarding maximum parking duration. In both cases, but especially the latter one, parking enforcement is a necessary complement of the policy. Since the goal of this scenario is to maintain the 'parking rights' of Tel Aviv residents, the regulations will only apply to visitors from outside the central area and/or from outside the city.

Main street scenario: Goal of this scenario is to create maximum turnover along main streets in order to improve the accessibility by car of the shops, bars and restaurants along these main streets. The underlying assumption is that visitors of an establishment along the main street would want to park along the main street. The existing 'parking rights' of Tel Aviv residents are reduced on the main streets, i.e. they will lose existing privileges with regard to these parking places. Depending on the tool that is used to increase turn-over, residents of the central area will either have to pay the 'market' price or live up to the limitations set with regard to parking duration. For residents living on the main streets themselves, some variations in this scenario are possible regarding the period in which the regulations apply. E.g. these residents could be allowed to park for free or without parking limitation from a certain hour in the evening onwards. Furthermore, this could be applied to the whole main street or only to designated stretches.

Visitor scenario: Goal of the scenario is to create *maximum probability* of finding a free parking spot for short-term visitors to establishments located along the main streets (residents and non-residents). Underlying assumption of this scenario is that the main street will not be able to provide enough capacity to serve all short-term visitors (less than an hour). The scenario thus introduces changes in on-street parking conditions in adjacent streets, as well as on conveniently located off-street parking lots. Parking regulations in adjacent streets, within convenient walking distance, will be identical to those along the main street. Prices for off-street parking will be reduced to stimulate long-term parkers to make use of them. Furthermore, residents will be offered cheap parking places on off-street lots, to reduce the negative impacts for them. In addition, parking limitations on side-streets could be loosened in periods of lower demand (e.g. later evening hours).

Local scenario: As an example of the local scenario, we consider the construction of a multi-level underground garage, where all places will be for sale to the local residents.

As a first try-out, the local scenario has been applied to the Basel neighborhood, a densely built, mixed-use, neighborhood, located in the old center of Tel Aviv. The municipality is considering to allow the construction of an underground parking garage in the area, to reduce parking problems for local residents, who complain on a regular basis about the lack of parking. The goal of the municipality is to ease the parking pressure for residents and reduce the number of complaints. In order to guarantee this, the municipality wants to make sure that there will be 'sufficient' parking levels, and hence parking places, in the new garage. The developer, in contrast, wants to be certain that 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 dedicated private parking places, the rough estimate of the residents' demand for on-street parking per km² is 8,000 cars, with a supply of about 7,000 places. That is, the demand for parking amounts to about 1.15 cars per parking place. In the field survey we estimated that about half of residents stays in the area during working hours., This implies that about 4000 cars per km² will arrive into the area and search for a parking place at the end of the day.

To estimate the “acceptable” distance between the on-street parking place and the driver’s place of residence, we recorded the plate numbers of 1,000 cars parking in the Basel neighborhood at night, and obtained the drivers’ addresses through the Israeli Central Bureau of Statistics. Combining both datasets, we estimated that none of the cars recorded in the survey parked further than 250 m air distance (5-minutes walk) from the driver’s residence. We thus concluded that despite the lack of parking space, residents continue their parking search either until finding an on-street parking at an acceptable distance from their residence, or 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 area, we studied a series of scenarios, in which the capacity, as proposed by the municipality, is set to 200 places. The simulations aimed at estimating the influence of additional parking places on the drivers whose destination lays in each of three concentric street blocks around the new lot (Figure 5). We investigated the critical period between 17:00 – 19:00, when 50% of the on-street parking places are left by visitors and about 4,000 residents arrive back home and compete for these places.



Figure 5. Snapshot of the initial model map screen (at 17:00) with three regions around the new parking lot. Black and yellow points along the streets denote parking cars, of residents and visitors, respectively.

As one could expect, 200 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 within the central area only (330 meter area in Figure 5), where 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 around 1,0, the drivers with destinations outside the central area neutralize the effects. The consequence is that both search time and average distance between parking place and residence decrease by less than 5% in the central area, which will be hardly felt by the drivers. The characteristics that change essentially concerns the groups of drivers that search for “too long” and park “too far”. The strongest decrease occurs in the fraction of residents searching for parking for more than 10 minutes – the share of this group drops from ~15% in the “no changes” scenario to 5% in the “200 new parking places” scenario.

Based on the model results, we conclude 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 terms of 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 meter in the dense Tel-Aviv center (an addition of about 1,000 parking places every 1 km²), the share of residents searching for more than 10 minutes for a parking space would drop considerably, with evident consequences regarding 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, i.e. 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 will eager to buy them. The decision about the size of the parking garage has thus been reduced to an economic rather than a transport issue.

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