



## GIS-based method for assessing city parking patterns



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### ABSTRACT

Every car trip ends with a parking search and parking. However, current transportation research still lacks practical tools and methodologies to analyze parking needs and dynamics, which cannot be adequately performed at an aggregate level. This paper presents PARKFIT, a novel algorithm for estimating city parking patterns that is based on a spatially explicit high-resolution view of the inherently heterogeneous urban parking demand and supply. Using high-resolution data obtainable from most municipal GIS, we apply PARKFIT to evaluate the fit between overnight parking demand and parking capacity in the city of Bat Yam, both currently and within the framework of the Bat Yam 2030 transportation master plan. We then analyze PARKFIT's capabilities and limitations, and supply PARKFIT as a free ArcGIS-based software.

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### 1. The problem of estimating parking capacity in heterogeneous city

Parking management is an underdeveloped transportation subject. Until very recently, most of the car transportation research investigated trips between the origin and destination and did not consider parking as a specific component of a trip. Land-use planners and decision-makers could not avoid dealing with parking planning, but did that on their own, with limited research to rely on. As a result, until the mid-1990s, the prevailing view was that the growing car ownership should be accompanied by a proportional growth of parking supply (Willson, 2013).

During the last two decades, the situation has been changing. City authorities finally understood that they cannot continue expanding their parking facilities, and the paradigm of “maximal parking supply” that uses limitations to parking to encourage people to use public transport has become dominant (Kodransky and Hermann, 2011). No matter how parking limitations are imposed – by means of spatial restrictions, or price, the consequences of these limitations are complex (Shiftan, 2002; Shiftan and Golani, 2005; Vaca and Kuzmyak, 2005; Litman, 2011). Increasing parking fees over wide areas causes, usually, strong public criticism, while local changes just encourage drivers to search for parking further away from the desired destination, thus shifting parking congestion to areas where the parking situation was considered balanced.

Therefore, assessing the influence of existing or planned constraints and regulations on parking availability demands accounting for the high-resolution heterogeneity of the urban parking space. This heterogeneity is often ignored by planners and their manuals that are still based on aggregate measures of demand and supply (Willson, 2013).

Both parking demand and supply vary in space and in time and are defined by the turnover, traffic limitations, drivers' preferences and their knowledge about local parking facilities. Understanding and estimating the intensity and location of gaps between parking demand and supply are critically important elements in analyzing parking patterns. A variety of academic research is using models to investigate the complexity of parking problems and suggests ways to improve parking dynamics.

The majority of parking models investigate the relation between parking demand and parking fees. Economic models focus on the equilibrium state of the parking pattern. Shoup (2005, 2006) argues that on-street parking is underpriced, and suggests regulating its availability by varying the fees, with the aim of maintaining an occupation rate of 87.5% (one parking place of eight is free). According to Shoup's model, this will provide a search time of close to zero. Calthrop and Proost (2006) suggest eliminating the competition between on- and off-street parking market by raising on-street parking fees to match off-street fees. Arnott and Inci (2006) incorporate in their model the congestion caused by parking search and demonstrate how this congestion can be eliminated by increasing parking prices. Anderson and de Palma (2004) suggest making the price of on-street parking dependent on the local demand, and suggest a model for defining parking fees for a

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specific location. They investigate how fees should vary in space to regulate the spatial distribution of demand. D'Acerno et al. (2006) propose a less traditional view – drivers arriving from areas characterized by low public transportation accessibility would pay less than drivers arriving from areas of high public transportation accessibility. This pricing scheme, according to D'Acerno et al. (2006), will result in a decrease in travel time and improve accessibility. Arnott and Inci (2006) relate between parking prices and road congestion, and propose regulating the price of on-street parking based on the value of the road space that is used for parking.

Spatially explicit simulation models aim at understanding the dynamics of parking patterns. Thompson and Richardson (1998) simulate a driver's choice between on- and off-street parking within a neighborhood of two-way streets, and demonstrate that the driver's decisions while searching for parking, result in non-optimal search behavior. Gallo et al. (2011) explicitly represent road network and parking facilities to study the effects of drivers' parking preferences and cruising on the traffic in the area. Their model estimates the correlation between the increase in the parking occupation rate and the level of road congestion. However, Li et al. (2007) present a conceptually similar model that includes public transport in addition to private cars, demonstrating that the relation between parking supply and the level of road congestion is more complex and in some cases the increase in parking supply can induce increased congestion. Recently, we proposed tackling the problem of predicting parking dynamics in a city with PARKAGENT, a spatially explicit, high-resolution simulation model of parking search (Benenson et al., 2008; Martens et al., 2010; Levy et al., 2013; Levy et al., 2015). The urban space is presented in PARKAGENT at a resolution of parking places, and every autonomous agent behaves as a driver that searches for parking in the vicinity of its destination, taking into account its knowledge of the area, time budget, and willingness to pay. The driver agent reacts to the traffic conditions within the search area, the parking situation, and the behavior of other drivers. PARKAGENT provides fundamental dependencies of the parking search time and distance between the parking place and destination on the occupation rate and turnover. We will exploit these dependencies obtained in PARKAGENT when analyzing the results of this paper.

Basically, agent-based models are able to incorporate heterogeneous demand and supply on the one hand and drivers' parking search behavior, including reaction to prices during parking search, on the other. However, the availability of data on these two major components is different. Spatially explicit estimates of the parking demand and supply patterns are adequately represented by standard layers of the municipality GIS. Estimates of parking demand can be obtained from the buildings layer, where buildings are characterized by the number of floors and their use. The layer of street segments, characterized by road type, parking permissions, parking zone, and the layer of off-street parking lots provides information on parking supply and, often, parking fees. If the data on demand and supply is insufficient, it can be completed and verified based on aerial photos and one-time field surveys. Data on drivers' arrivals, departures, and on drivers' parking search behavior in particular, demand essential investment in field surveys and interviews and in some cases will simply not be available. This paper focuses on the problems that can be satisfactorily investigated despite the lack of behavioral data. We aim at "fast and frugal" estimates of the goodness of fit between the projected parking demand and supply and develop for this purpose a simple software tool – PARKFIT that accounts for the spatial heterogeneity of the parking situation without necessitating investment in field surveys.

This paper aims at presenting and investigating PARKFIT, a method and software application. Our approach exploits standard

GIS datasets that are widely available in the majority of Western municipalities, as is the case in our example application in the city of Bat Yam. The Bat Yam area is ca. 8.0 km<sup>2</sup>, and its population of about 130,000 resides in 3300 buildings with a total of 51,000 apartments. The city has a common boundary with Tel Aviv and is located to the south to it. Part of the boundary area (close to the sea) is not populated, while the rest of the boundary is a highway that is inconvenient for crossing. At the east, the city is bounded by the wide highway. That is, for the analysis of parking processes, Bat Yam can be considered as an isolated area. In Section 2, based on Bat Yam's municipal GIS, we make the step from aggregate to high-resolution data on parking demand and supply. Section 3 introduces the PARKFIT method. Section 4 is devoted to the validation of PARKFIT and estimating its basic parameters that we consider common for similar cities. In Section 5 we apply PARKFIT for estimating Bat Yam's parking capacity nowadays and in the future, as a part of the Bat Yam 2030 transportation plan. Finally, we discuss the proposed method and results in Section 6.

## 2. High resolution GIS as a source of data on parking demand and supply

At the most aggregate level, the parking pattern in a specific area is defined by the ratio  $R$  of the demand  $D$ , expressed by the overall number of cars that are willing to park there, and the parking supply  $S$ , expressed by the overall number of existing parking places in the area:  $R = D/S$ .

If demand and supply are distributed in space uniformly, then for  $R > 1$ , the value of  $(R - 1) * S$  is the number of parking places that the area lacks in order to accommodate all drivers wanting to park there, while for  $R < 1$ ,  $(1 - R) * S$  is the number of vacant parking places in the area.

To provide a spatial framework for this aggregate view, let us consider overnight parking in a city where each building  $b$  accommodates  $D_b$  car owners and parking is possible on street only. Let us associate each parking place to its closest building, and denote the number of parking places associated with building  $b$ , as  $S_b$ . Let the highest value of the demand-to-supply ratio  $R_b = D_b/S_b$  that is observed for all buildings in the city be observed for the building  $b_0$  and equal to  $R_{b_0} = D_{b_0}/S_{b_0}$ . While  $R_{b_0}$  remains below 1, the drivers in the area will easily find an overnight parking place in the vicinity of their destinations, and the overnight parking pattern will consist of non-overlapping clusters of cars around destinations of their drivers.

Starting from  $R_{b_0} > 1$ , parking places that are associated with the buildings adjacent to  $b_0$  will be used by drivers aiming at  $b_0$ . Those arriving late will find  $S_{b_0}$  parking places occupied, and so they will park at a place associated with one of the adjacent buildings. The  $b_0$  residents will thus cause a chain reaction (Levy et al., 2013) – some of the drivers arriving late to the destinations adjacent to  $b_0$  will also have to park beyond the vicinity of these buildings. The phenomenon will become stronger with the increase in the number of buildings  $b$  for which  $R_b > 1$ , and accelerate the growths of the average parking distance to the destination (Levy et al., 2013).

We can thus conclude that in reality, where demand and supply vary over urban space and in time, the aggregate demand-to-supply ratio  $R$  is evidently insufficient. One can consider a parking supply in the city as sufficient based on a misleading aggregate value of  $R < 1$  calculated over the entire city, whereas in reality the majority of the demand can be concentrated in the city center, while the majority of supply is scattered on the outskirts. Parking lots on the one hand, and office buildings that attract numerous visitors on the other, further increase the

heterogeneity of the parking demand and supply patterns, and the potential lack of fit between them.

The obvious first step toward accounting for spatial heterogeneity of parking demand and supply is to partition the city space into smaller parts, such as census areas, traffic analysis zones, or city blocks, and estimating the demand-to-supply ratio  $R$  for each unit of this partition. Fig. 1 presents the estimates of parking demand, supply, and demand-to-supply ratio for the city of Bat Yam, by its 219 city blocks.

As can be seen in Fig. 1, the view of parking demand and supply at a resolution of city blocks provides essentially discontinuous maps and provides an initial view of parking demand/supply heterogeneity. However, blocks' boundaries are, evidently, not respected by the drivers when they search for parking and park. The use of aggregate data is even more problematic when analyzing the effects of local changes in parking demand or supply. An adequate view of parking search and parking patterns should reflect the drivers' continuous view of space. This, in turn, demands high-resolution information on demand and supply.

A driver's decision on where to park is based on the location of the destination and the availability and location of nearby parking options. Thus, the necessary resolution for proper analysis is that of a single destination and a specific parking place. Drivers' destinations are represented by buildings – residential, office, or commercial; and open areas – parks and gardens. The parking supply consists of private and public parking lots, on-street parking places, and dedicated parking related to dwellings and offices. Nowadays, this information is easily available – a typical municipal GIS contains sufficient information for estimating parking demand and supply via the data stored by the GIS layer of buildings characterized by use, floor area, and number of floors; layer of parking lots characterized by capacity; and layer of street segments characterized by on-street parking regulations. In Fig. 2 we present the information on parking demand and supply for the city of Bat Yam at a resolution of buildings and street segments, based on the available layers of the Bat Yam municipal GIS.

The layer of buildings and buildings' attributes (Fig. 2a) allows us to estimate the number of drivers who aim to park near each building. These estimates are based on the number of

apartments/families per residential building, the number of jobs per office building, and the number of customers per shopping mall. Based on the layers of streets and parking lots (Fig. 2b) we are able to estimate the parking capacity of each road segment. Fig. 2c and d presents the distributions of these characteristics. The view of the parking demand becomes more precise when information on registered addresses of car owners is available, while information regarding on-street parking regulations and fees may improve the view of the parking supply.

This high-resolution view of drivers' destinations and parking options opens new perspectives for estimating the balance between parking demand and supply. In what follows, we present a new method for combining high-resolution GIS data on parking demand and supply into spatially explicit estimates of an area's parking capacity. The method can be applied to various parking situations in any spatial surroundings, while in this paper we present its basic version that focuses on the residential overnight parking. In case of overnight parking, destinations are associated with residential buildings, and parking regulations for residents define the attractiveness and availability of the different parking options. The necessary data regarding on-street parking regulations and the capacity of parking lots are available for the cities of Tel Aviv and Bat Yam, where we conduct experimental work employing our methodology.

### 3. The method for estimating parking capacity pattern

The proposed method for estimating a city's parking capacity mimics the outcome of the parking search by distributing the demand of every destination among the available parking facilities around that destination accounting for the drivers' competition. We call this method PARKFIT. PARKFIT employs a Monte Carlo approach to estimate the average distance between the cars aiming for a specific destination and the destination, and the fraction of cars that fail to find a parking place. PARKFIT is implemented as an ArcGIS 10.2 Python application, and is freely available for download at (Levy and Benenson, 2015).

Let us denote parking places as  $p_i$ ,  $i = 1, 2, \dots, I$ , destinations as  $d_k$ , and the destinations' demand for parking as  $D_k$ ,  $k = 1, 2, \dots, K$ .

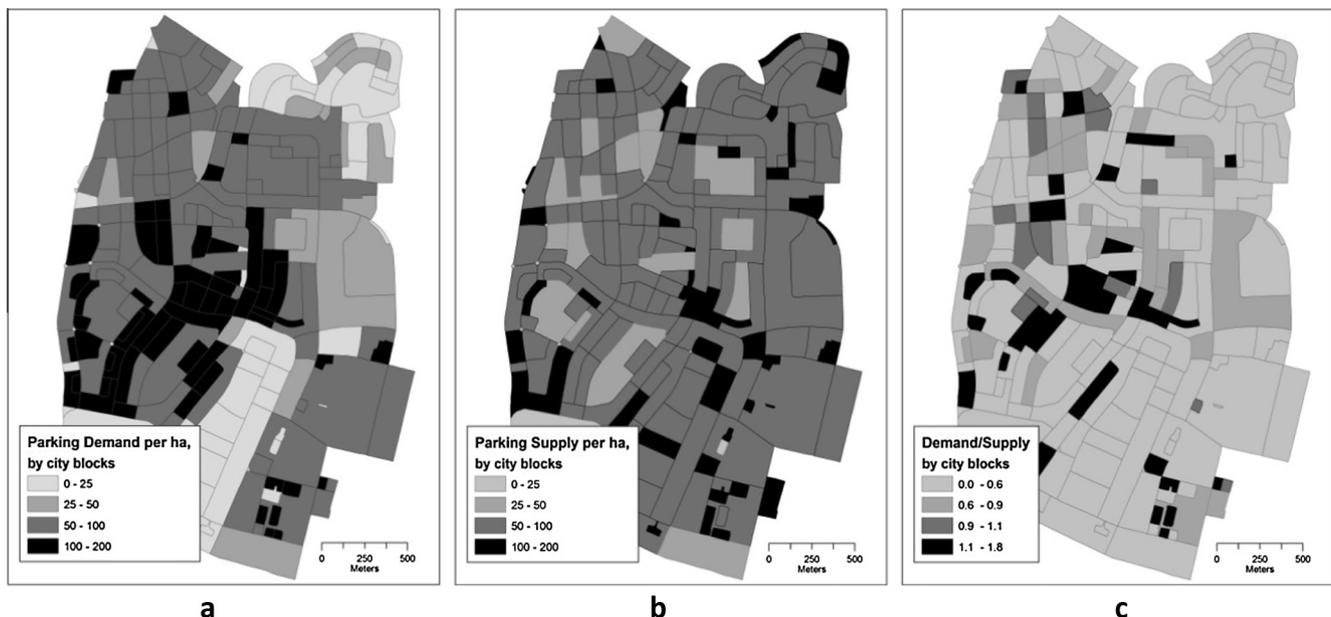


Fig. 1. Characteristics of overnight parking for the city of Bat Yam partitioned into 219 city blocks: (a) parking demand per ha, (b) parking supply per ha, and (c) demand-to-supply ratio.

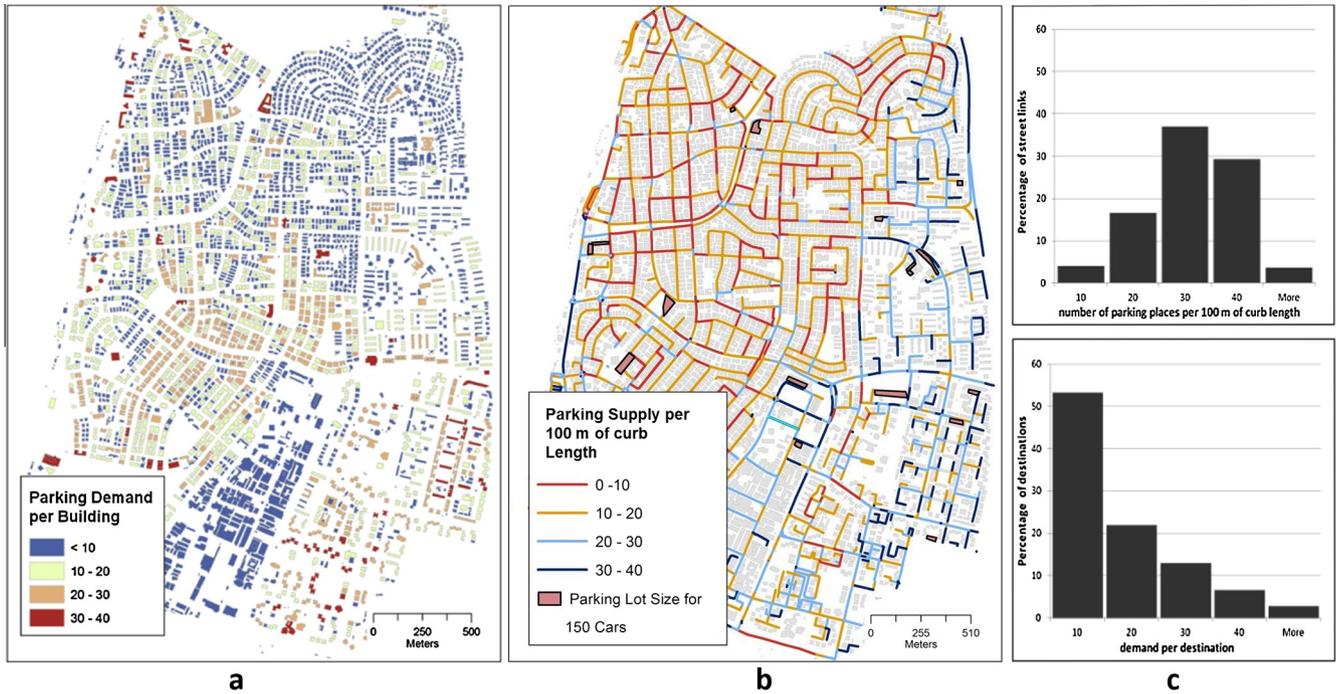


Fig. 2. (a) Parking demand per building, (b) number of parking places per 100 m of curb, and (c) non-spatial distributions of these parameters.

Let  $r_{max}$  be maximal distance acceptable to drivers between the parking place and the destination. This distance is estimated in field studies (Section 4 below).

Stage 1: Establishing parking demand, parking supply and randomizing arrivals.

1. Based on demand  $D_k$  at every destination  $d_k$ , construct the list of demand, DEMANDLIST, in which each destination  $d_k$  is repeated  $D_k$  times. Let  $D_{total} = \sum_k D_k$ , be the total demand.
2. For each destination  $d_k$ 
  - a. Construct list  $P_k$  of parking places in the area at a distance less than  $r_{max}$  from  $d_k$ . Order this list by the distance between the parking place and  $d_k$ .
  - b. Set empty list of parking places  $O_k$  to store information about parking places occupied by drivers whose destination is  $d_k$  and the distances between these parking places and  $d_k$ .
  - c. Set variable  $F_k = 0$  to store the number of drivers who aim at  $d_k$  but failed to park at a distance less than  $r_{max}$  from it.
3. Randomly reorder DEMANDLIST. Let  $d_{(1)}, d_{(2)}, \dots, d_{(1)}, \dots$  be the resulting order of destinations.

Stage 2: Simulation of parking occupation.

4. Consider the next destination  $d_{(1)}$  from the DEMANDLIST:
  - a. Set  $d_{(1)}$  as the destination of driver A arriving to the area
  - b. If  $P_{(1)}$  is not empty, then
    - Choose the first parking place  $p$  from the  $P_{(1)}$  list (it is closest to  $d_{(1)}$ ) and allocate it to A
    - Add to  $O_{(1)}$  pair  $(p, \text{dist}(p, d_{(1)}))$ , where  $\text{dist}(p, d_{(1)})$  is the distance between  $p$  and  $d_{(1)}$
    - Delete  $p$  from all lists  $P_k, k = 1, 2, \dots, K$
  - Else
    - Set  $F_{(1)} = F_{(1)} + 1$ .

The outcome of the PARKFIT algorithm consists of:

- $K$  lists  $O_k$  of parking places occupied by the drivers who aimed at  $d_k$  and succeeded to park closer than  $r_{max}$  from  $d_k$  and the calculated distances between these parking places and  $d_k$ .
- $K$  values of  $F_k$  - number of drivers who aimed at  $d_k$  but failed to park at a distance below  $r_{max}$  from  $d_k$ .

Note that

1. In case of  $R \ll 1$ , PARKFIT pattern represents clusters of  $D_k$  parking places that are closest to destinations  $d_k$ .
2. Randomization of destinations in the DEMANDLIST (step 3 of stage 1) entails different results in every repetition of the PARKFIT algorithm. These random effects are important when the demand-to-supply ratio is approaching 1 and drivers arriving first have an obvious advantage over drivers arriving later. To estimate the effects of random drivers' arrival, the PARKFIT simulation should be repeated many times. The results of this paper are based on 1000 repetitions.

In what follows, we focus on two parameters that define drivers' satisfaction:

- (1) *Parking distance* - The distance between the parking place and the destination.
- (2) *Probability of parking failure* - probability of failing to park within an acceptable walking distance from the destination.

We estimate the PARKFIT parameters, and calibrate and validate the algorithm based on the Bat Yam and Tel Aviv data. Both cities are separated from the other cities of the Tel Aviv metropolitan by highways and Bat Yam is adjacent to and south of Tel Aviv. The demand-to-supply ratio in Bat Yam center is close to 100% while in Tel-Aviv this ratio, for some neighborhoods, is even above 100%. PARKFIT is further employed in Bat Yam for assessing the parking development plan of the city transportation plan for 2030.

#### 4. Field estimates of the maximal parking distance

In regard to residential overnight parking, we attempted to estimate the maximal parking distance in two field surveys, one in Bat Yam and one in Tel Aviv. Both surveys were performed between 24:00 and 05:00 during the working days of the week. During the surveys, cars' exact location and license plate number were recorded and submitted to the Israeli Central Bureau of Statistics (ICBS). ICBS personnel retrieved the registered address of each car owner according to the plate number and calculated the aerial distance between the location of each parked car and its owner's address. For the reasons of personal privacy, the ICBS supplied the list of aerial distances between the parking location and owner's address disconnected from the list of plate numbers.

In the Tel Aviv night survey, the location of ca. 4000 cars parked overnight were recorded within the Basel residential area ( $\sim 2 \times 2$  km) during 10 workday nights of two consecutive weeks. The demand-to-supply ratio for this area is very high, about  $R = 1.15$  (Benenson et al., 2008) that is, all physically feasible and free of charge parking places are occupied there at night and the surplus of residents have to pay for parking in municipal or private parking lots nearby. In  $\sim 10\%$  of cases, information on registered address was not useful because the cars were owned by commercial or rental companies.

The Bat Yam survey was less extensive – locations of 350 cars were recorded over an area where the average demand-to-supply ratio is about  $R = 0.76$ . Addresses were successfully identified by the ICBS for 220 car owners, the rest of the cars were registered to commercial companies or leased.

All cars in both surveys had local parking permits that are provided to city residents only, permitting free on-street parking. Nonetheless, as shown in Fig. 3, a fraction of cars in both surveys parked far away from the registered address of the owner. In Tel Aviv 1300 cars (35%) parked at a distance of 3 km or further from the owner's address (Fig. 3a). In Bat Yam, this phenomenon is weaker, but yet 15% of cars were parked at a distance further than 600 m from the owner's address.

A distance of several kilometers between a car parked in the Basel area and the registered address of its owner may suggest that the owner's address, as recorded by the Israel Ministry of Transport, and driver's destination during the period of the survey are different. The survey conducted in the Basel area makes it possible to verify this phenomenon: If during the period of the survey

the overnight destination of a driver is different from the address of the car owner, then this car should repeatedly be found parked far away from the registered address during the survey nights.

This was indeed the case. Of the 4000 cars recorded in the Basel area during 10 survey nights, 3000 were recorded more than once, and, as can be seen in Fig. 4, the registered address of the owner of many of these 3000 cars is steadily far away from their overnight parking places in the Basel area.

As can be seen in Fig. 4a, if a car parked at a distance of 400 m or higher from the owner's address one night, then the same relatively far distance remains true for all nights. This is not so for distances below 400 m (Fig. 4b and c). Splitting the distances by bins of 100 m clearly demonstrates that once this distance exceeds 400 m, the driver does not park any closer to the owner's registered address; in other words, the driver's destination during the survey period is evidently different from the address registered at the ICBS. We thus conclude that despite an extremely high demand-to-supply ratio, residents of the Basel neighborhood are not parking at aerial distances of more than 400 m ( $\sim 10$  min walk) from their destination. Based on this result, we apply  $r_{\max} = 400$  m in PARKFIT applications further in this paper.

#### 5. Using PARKFIT for estimating Bat Yam parking capacity in 2030

The data from the Bat Yam high-resolution municipality GIS and the results of the field surveys are sufficient for applying PARKFIT to estimate the current Bat Yam parking capacity and to predict the parking pattern in 2030 (as part of the 2030 transport development plan for the city). Based on these data, high-resolution GIS maps of parking demand and supply have been constructed.

##### 5.1. Mapping current parking demand and supply in Bat Yam

###### 5.1.1. Parking supply

We performed an extensive overnight and daily field survey of the parking supply in Bat Yam in June 2010. Surveyors collected data on the parking regulations, on-street parking places and on the capacity of the off-street parking lots. Parking occupancy was registered at different times of the day. The number of dedicated parking places, available to residents of the building was also surveyed. It is important to note that all parking lots in Bat Yam

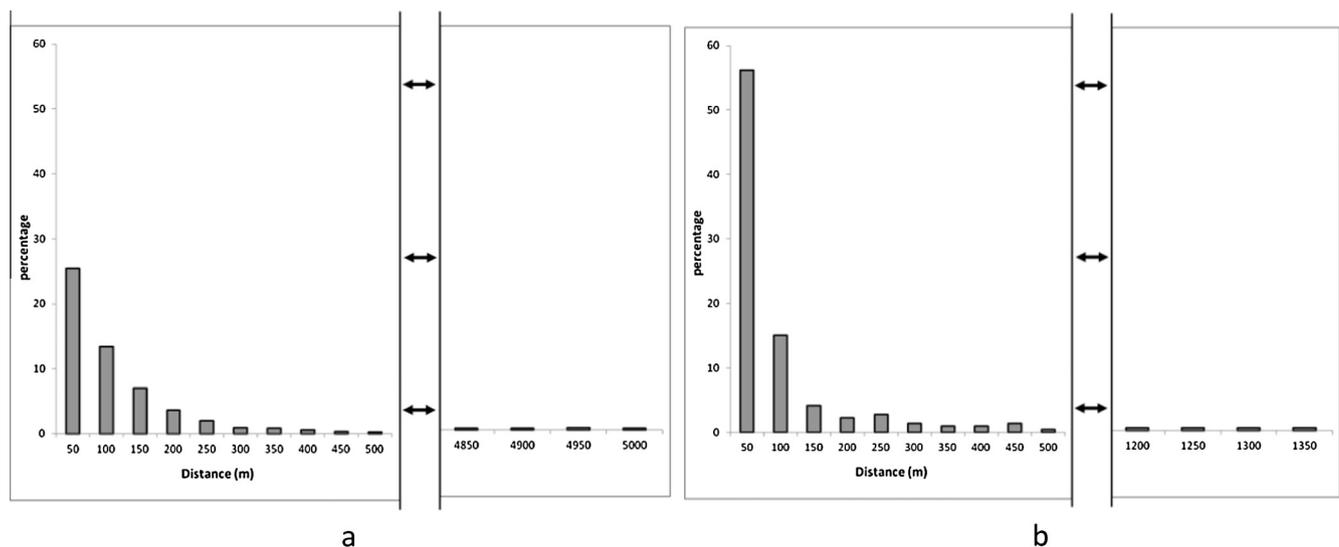


Fig. 3. The distribution of aerial distance between the overnight parking place and the car owner's address in (a) Tel Aviv and (b) Bat Yam.

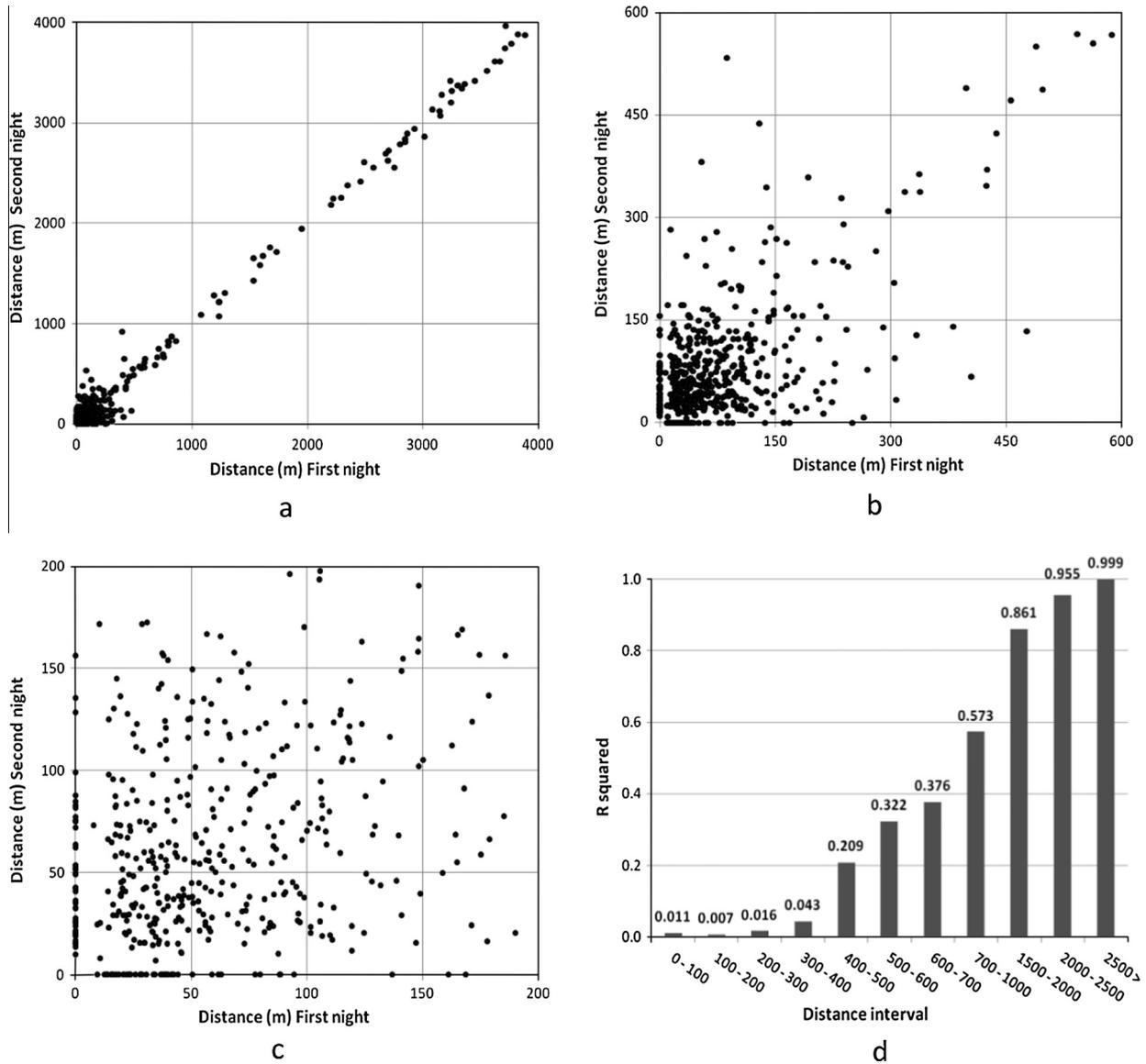


Fig. 4. The distance between the car owner's address and parking place on two consecutive nights for (a) all cars, (b) cars parked at distances less than 600 m, (c) less than 200 m, and (d) dependence of the  $r^2$  for the parking place – the distance by 100 m intervals.

are free for overnight parking of Bat Yam residents. Illegal parking was rarely observed in the night surveys and we ignore it.

Initially, the number of on-street parking places per each street segment was estimated based on the municipal GIS layer of streets (see Fig. 2b above), assuming that parking is prohibited by law within 3 m of an intersection. Note that the average length of a car in Israel is 4.5 m and the average interval between two parallel parked cars is 5.0 m. The average interval between two perpendicular parked cars is half, 2.5 m, similar to the standards of the Israel Ministry of Transport (2005).

The map of parking facilities was improved and verified, based on high-resolution aerial photos in which the color of the road curb that designates permitted/prohibited on-street parking is easily recognized. According to the aerial photos, about 30% of the curb is permitted for 90° or diagonal parking, while the rest is for parallel parking. The overall number of on-street parking places in Bat Yam is ca 27,000. Total number of off-street parking places in parking lots and in the parking spots that are dedicated to residential buildings is close to 19,000 which results, on average, in 19,000 pp/3300 bldg  $\approx$  5.8 pp/bldg. Together with parking lots

and dedicated parking places, the total number of parking places in the city is close to 46,000.

### 5.1.2. Parking demand in Bat Yam

According to the Bat Yam municipality GIS, the number of buildings in the city is 3300, and the number of residents' cars in the city in 2010 was ca. 35,000. That is, the average car ownership  $C$  in the city is about 35,000/51,000  $\approx$  0.69 car/apt or 35,000/3300  $\approx$  10.6 car/bldg, and the average demand-to-supply ratio  $R$  is equal to 35,000 car/46,000 parking place  $\approx$  0.76 car/pp.

### 5.2. Using Bat Yam field data for validation of PARKFIT

We apply PARKFIT to generate the distribution of the distances between the overnight parking place and destination in Bat Yam. Based on Bat Yam's car ownership rate of  $C = 0.69$ , we estimated the number of cars in each building as the nearest integer to the number of apartments multiplied by 0.69, and compare the PARKFIT results with the field survey results described above. As

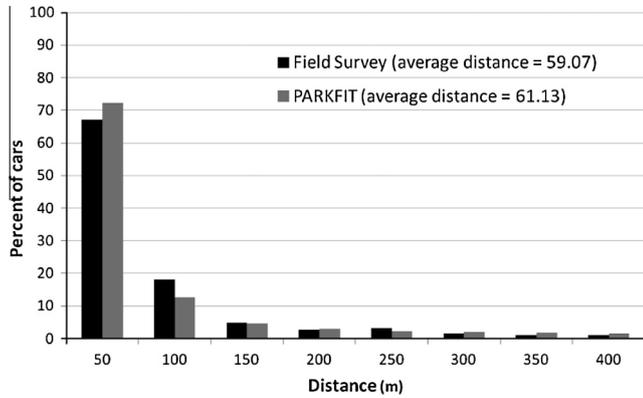


Fig. 5. The distance between overnight parking place and destination for cars parked less than 400 m from their destination, comparison of PARKFIT and Bat Yam 2010 field survey results.

can be seen in Fig. 5, the distributions from PARKFIT and the field survey are very similar ( $\chi^2 = 2.78$ ,  $df = 7$ ,  $p > 0.9$ ).

5.3. Predicting Bat Yam parking capacity in 2030

As a part of the Bat Yam city master plan of transport development, Bat Yam’s parking capacity estimates for 2030 are based on ICBS projections of the Bat Yam population and car ownership at a resolution of the city’s 39 statistical zones.

According to the ICSB, an additional 19,000 apartments are planned for construction in Bat Yam by 2030, and the population will increase by 50,000. Car ownership rate C in Bat Yam will increase from 0.69 car/apt in 2010 to 0.93 car/apt in 2030. The majority of new construction projects will include dedicated parking facilities and the total number of parking places in the city will increase from 45,000 to 67,000. That is, planned development will cause an increase in the global demand-to-supply ratio from

$R = 0.76$  in 2010 to  $R = 0.97$  in 2030. In what follows, we assume that parking regulations in the city will not be changed, and parking lots will remain free for the residents’ overnight parking. According to Fig. 6 there is a very different demand-to-supply ratio for many adjoining statistical areas, which necessitates a high-resolution analysis. Below, we present PARKFIT’s high-resolution analysis of Bat Yam’s parking situation today and in 2030.

Fig. 7 presents maps showing the distances between overnight parking place and destination for 2010 and 2030. On average, the distance to destination almost doubles by 2030, from 47 m to 83 m. For some areas, this distance increases to 150 m, while in other areas the increase is close to zero.

The estimate of the number of cars that fail to find parking at a distance of 400 m from the destination in 2010 is very low, comprising about 2% of all parked cars only (Fig. 8). In 2030, this fraction increases to about 7%.

5.4. Transforming parking places into public transportation

Located at the periphery of the Tel Aviv metropolitan area, Bat Yam citizens do not yet experience significant parking problems. However, this will not last for long. Looking forward, the Bat Yam Municipality is considering alternative ways of developing traffic infrastructure in the city, taking into account the trade-off between parking availability and the use of the public transport. One of the suggestions of the Bat Yam transport development plan is to designate the city’s main roads for public transport only. This change will result in the immediate canceling of ca. 2000 on-street parking places. To assess the consequences of this reduction, we applied PARKFIT to assess the distribution of distances between overnight parking place and destination in 2010, after the immediate implementation of this plan (Fig. 9).

As can be seen in Fig. 9, about 40% of destinations will be affected, but the increase in the distance between parking place and destination is minor, 9 m on average, with less than 3% of destinations (100 buildings) for which the distance increases more

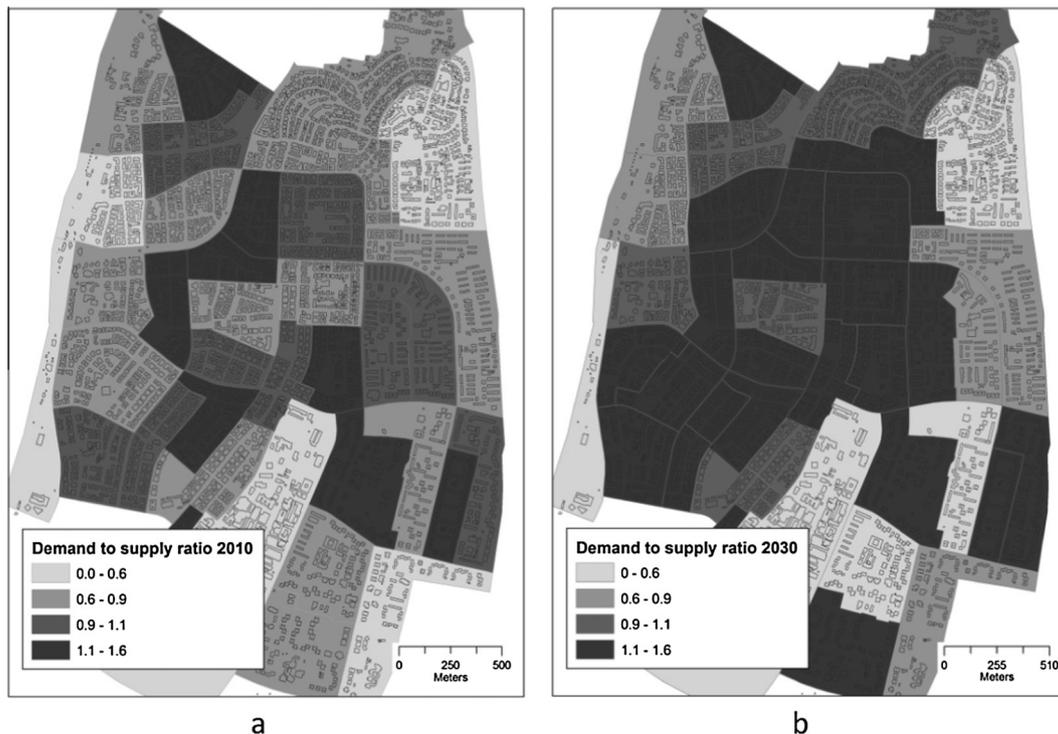


Fig. 6. Demand-to-supply ratio at a resolution of Bat Yam’s 39 statistical zones in 2010 (a), and in 2030 (b).

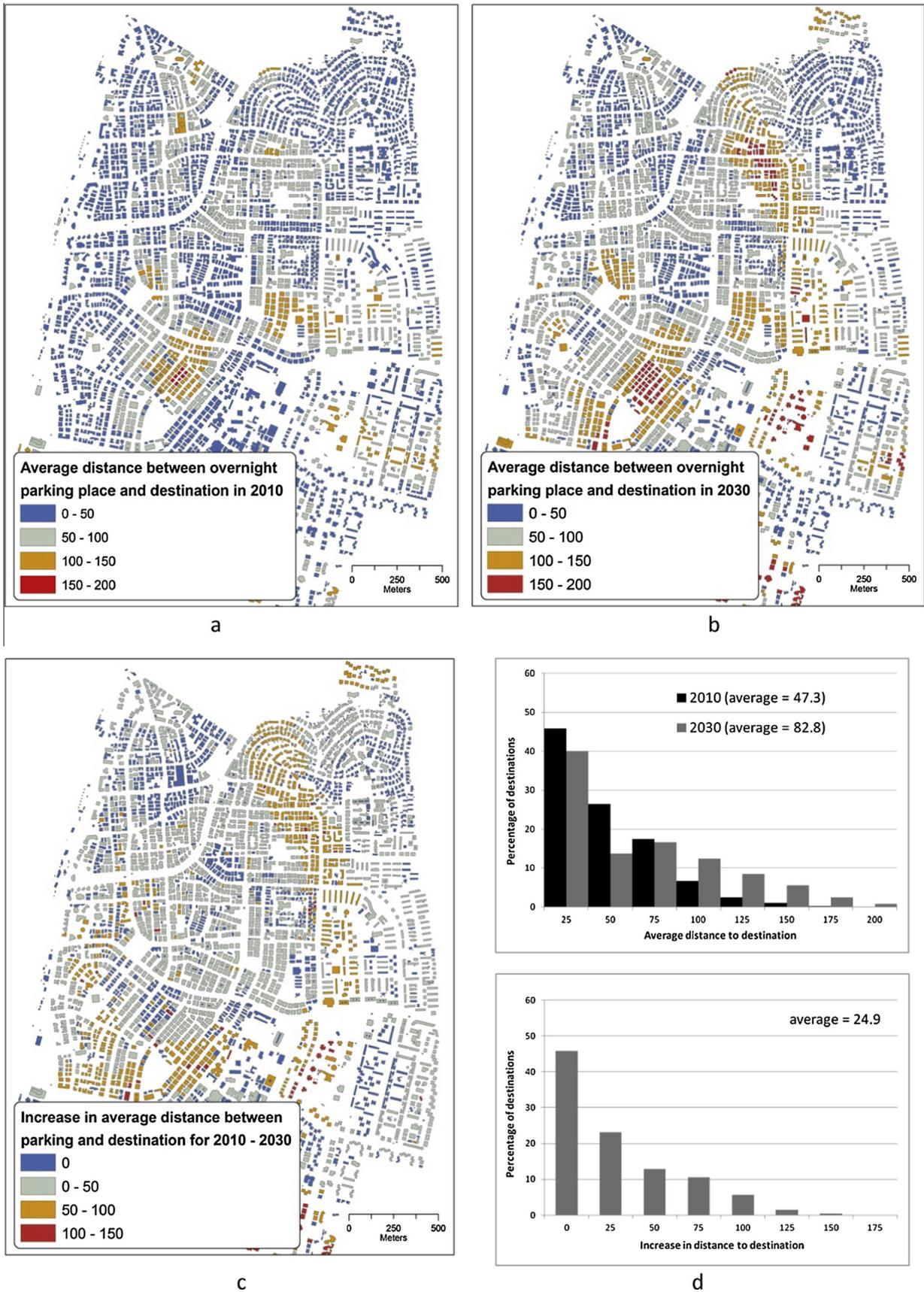


Fig. 7. PARKFIT estimation of average distance between overnight parking place and destination for (a) 2010 and (b) 2030, (c) the increase in average distance between 2010 and 2030, and (d) the distribution and averages of the distance between parking place and destination and increase in this distance between 2010 and 2030.

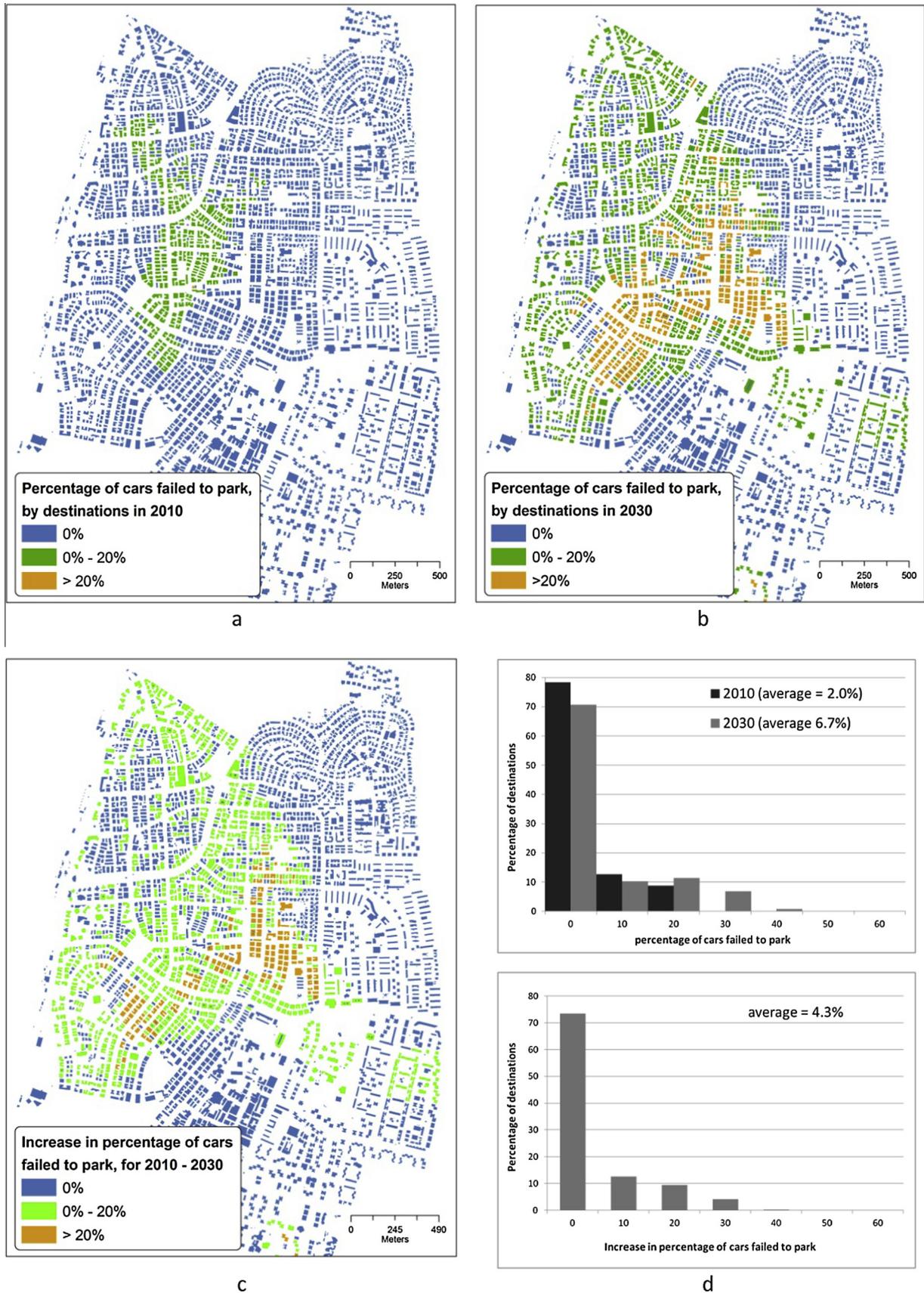
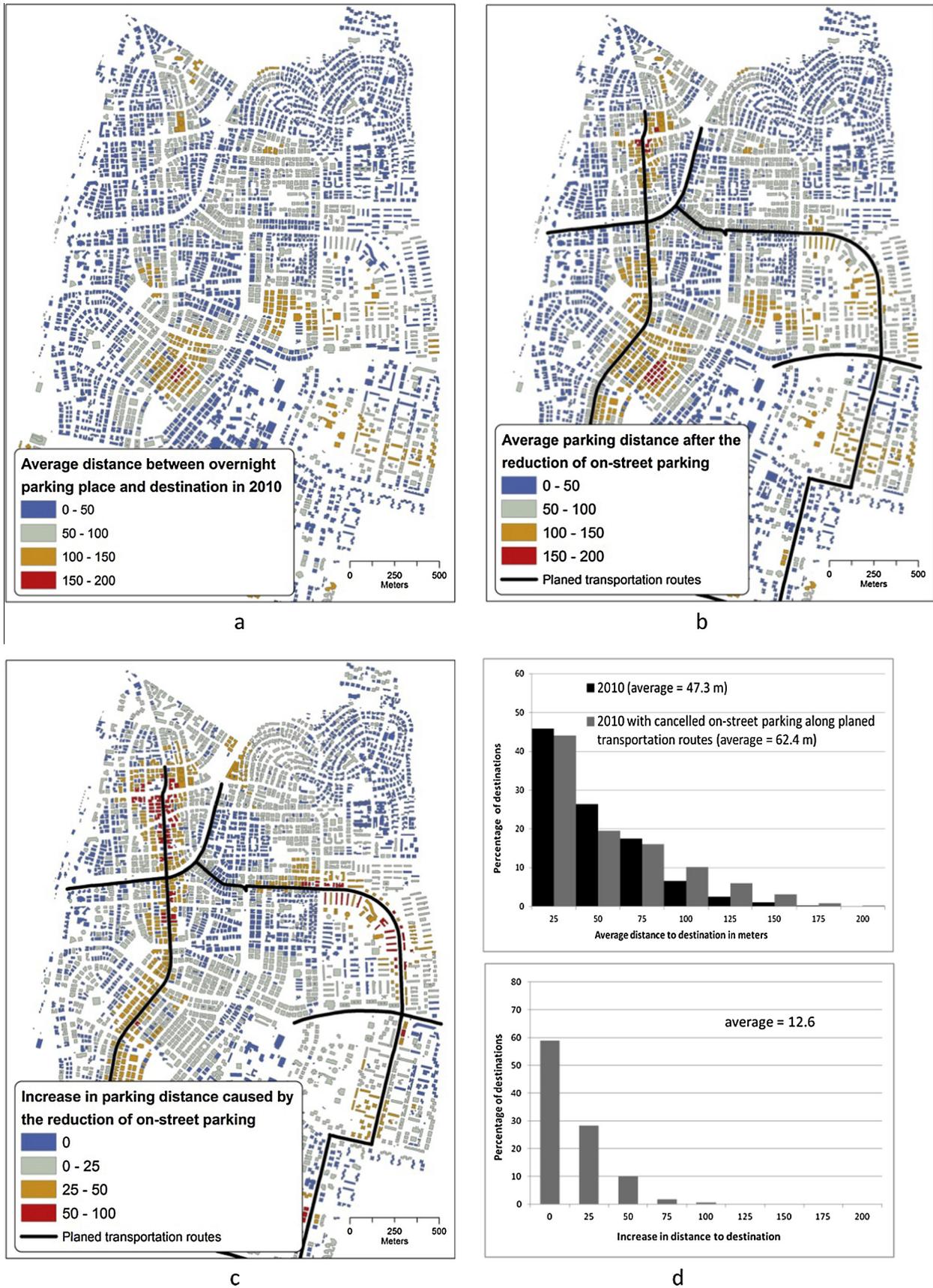


Fig. 8. PARKFIT estimation of the percentage of cars that failed to park within 400 m from their destination for (a) 2010 and (b) 2030, (c) the increase in the percentage of failures between 2010 and 2030, and (d) the distribution and averages of all three characteristics.



**Fig. 9.** Average parking distance (a) before the removal of on-street parking on main roads, and (b) after, (c) the resulting increase in distance between overnight parking place and destination, and (d) the distribution of the distance and the increase in distance after the reduction in on-street parking.

than 50 m. The fraction of cars that fail to park within 400 m of the destination does not change, and 95% of the destinations for which the distance increases by 50 m or more are located adjacent (<100 m) to the main roads designated for public transport only. The limited impact of this plan on the availability of parking and the lack of parking demand spillover can therefore be a key factor in favor of the city authorities accepting this alternative – the inconvenience of a longer walk for residents from the parking place to the destination will be balanced by the proximity to fast and efficient public transport.

## 6. Conclusions and discussion

In a homogeneous city, parking demand and supply are uniformly distributed in space and the parking pattern is defined by one main parameter – the global demand-to-supply ratio. In reality, the spatial distributions of the demand and supply are essentially heterogeneous, and this heterogeneity is critical for transportation management and planning. Wrong weighting of local and global factors can lead to unnecessary construction or, prevent development of needed parking facilities. PARKFIT can be applied in any city where standard high-resolution infrastructure GIS is available. PARKFIT provides a bridge between the global and local situations. Spatially explicit representation of the parking demand and supply enables recognition of areas of under- and over-supply, as well as estimating the distance between the parking place and the driver's destination. PARKFIT provides a unique hot-and-cold map of the parking patterns and the spillover effects related to high demand-to-supply areas. The obtained distribution of the distance to destination provides a reference point for the parking "level of service". These capabilities are essential for planning predictions and are used in the framework of the Bat Yam transportation plan for 2030.

Based on municipal GIS and on field data we have validated PARKFIT's estimates, demonstrated the use of PARKFIT for analyzing the current and future state of overnight parking in the city of Bat Yam and investigated the consequences of future parking regulation. This includes the average distance between the parking place and destination and the rate of parking failure in 2010 and in 2030, according to the projection of Bat Yam's population growth provided by the Israeli Central Bureau of Statistics. Lastly, we analyzed the reducing on-street parking along main roads that will be converted to transit-only roads. In the latter case, we found that the existing spatial structure of the Bat Yam streets and parking facilities prevent expansion of the emerging parking spillover and the reduction in on-street parking will affect only the buildings that are adjacent to these roads. Evidently, PARKFIT can be applied for assessing the consequences of restructuring parking facilities by any other reasons, e.g., for establishing bicycle lanes or pedestrian walkways.

PARKFIT has its limitations. First, to apply PARKFIT, one has to establish the maximal acceptable distance to parking  $r_{\max}$ . The 400-m limit that is employed in this paper is estimated based on the data collected in Bat Yam and Tel Aviv. Larger  $r_{\max}$  will cause the spread of the demand farther away from the destinations and thus decrease the rate of the parking failures and increase average parking distance. Second, the current version of PARKFIT does not incorporate important factors of parking pattern dynamics and drivers' behavior: turnover, tradeoff between the price of parking and walking distance to destination, and local factors of drivers' parking choice, as security or road crossing during the walk. All this makes the current version of PARKFIT fit mostly for analyzing overnight residential parking. To eliminate these imitations, the next version of the PARKFIT algorithm will explicitly include turnover and an interface for establishing a tradeoff between the parking prices and walking distance to destination. Traveler's choices

between private cars and public transport remain beyond the PARKFIT framework.

One of the PARKFIT limitations demands specific note. Namely, the PARKFIT framework does not include parking search time. However, a rough estimate of this important parameter can be obtained based on the universal dependencies of the parking search time and average distance to destination on the occupation rate, as presented in our recent paper on the PARKAGENT model (Levy et al., 2013). Relating between the average distance to destination and average parking search time obtained for the same occupation rates (Levy et al., 2013, Figs. 4 and 6), one can deduce that the average cruising time is close to zero when the average distance between the parking place and destination is less than 50 m (practically, this means that a driver parks on the road segment that is adjacent to his or her destination). For higher distances, the average cruising time increases linearly with the increase in the parking distance and reaches 4.5 min when the average distance reaches 200 m. That is, roughly, once the average distance between parking place and destination exceeds 50 m, each additional 50 m adds another 1.5 min to the average parking search time.

To conclude, every real-world problem demands a series of tools that exploit different sources of knowledge about the phenomenon being studied. The parking phenomenon is critically defined by the heterogeneity of demand and supply on the one hand, and of human behavior on the other. In these respects, the PARKFIT approach and software build on the first component – explicit knowledge of the heterogeneity of the phenomenon's spatial component. Incorporation of human behavior demands an agent-based approach that is implemented in the PARKAGENT model (Benenson et al., 2008; Levy et al., 2013; Levy et al 2015). Taken together, PARKFIT and PARKAGENT may serve as a starting point for establishing a set of operational tools for parking management and planning.

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