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The benefits of a high-resolution analysis of transit accessibility

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ABSTRACT

Accessibility is an important consideration in sustainable mobility policies, particularly for transit users. Measures suggested in the literature are based on coarse aggregate spatial resolution of traffic analysis zones that is sufficient for managing car travels only. To reflect a human door-to-door travel, transit accessibility demands an explicit view of the location of origin, transit stops and destination, as well as of the temporal fit between transit lines timetable and traveler's needs. We thus estimate transit accessibility based on mode-specific travel times and corresponding paths, including walking and waiting, at the resolution of individual buildings and stops. Car accessibility is estimated at a high resolution too. A novel representation of transit network as a graph is proposed. This representation includes all modal components of a transit travel – walking, waiting at a stop, transit ride, transfers between lines, thus enabling unified view of a travel, regardless of mode. The use of modern high-performance graph database allows construction of high-resolution accessibility maps for an entire metropolitan area with its 100–200 K buildings. The application is tested and applied in a case study involving the evaluation of the 2011 bus line reform in the city of Tel Aviv. Specifically, we demonstrate that while the reform increased the average accessibility for the entire city the increase was not uniform with different areas of the city experiencing different absolute accessibility by transit and relative accessibility in comparison to car travel. The bus reform did in fact benefit travelers that experienced low relative accessibility, but the benefits are mainly accruing to longer trips. Our approach and computational methods can be employed for directly investigating the impacts of transportation infrastructure investments.

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Accessibility; transit; equity; high-resolution spatial analysis

> The accessibility experience of individuals in their everyday lives is much more complex than that which can be measured with conventional measures of accessibility. (Kwan 1999, p. 210)

1. Introduction

In recent years, we have seen growing interest of researchers, practitioners and policymakers in improving accessibility for goods and services in urban areas.

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Accessibility, defined broadly as the ease of access, is people's ability to reach necessary or desired activities using the available transportation modes (Handy and Niemeier 1997, Geurs and Ritsema van Eck 2001, Levine and Garb 2002). It is regarded as a key quality criterion to evaluate the functioning of the transport-land use system and the overall urban economy (Kenyon *et al*. 2002, Bristow *et al*. 2009). Furthermore, accessibility has been an integral part of sustainable development policies (Bruinsma and Nijkamp *et al*. 1990, Feitelson 2002, Kwok and Yeh 2004, Bertolini *et al*. 2005) and particularly in the domain of social inclusion and equity that assess how accrued benefits and burdens are distributed across society (Farrington and Farrington 2005, Lucas 2012, Martens 2012). Given the growing relevance of accessibility, it is clear that measuring it correctly and adequately is vital for effective and equitable land use and transportation planning.

In parallel to the rising importance given to accessibility in urban planning goals, there seems to be growing discomfort about how accessibility is primarily addressed in the literature as an objective (physical-financial) construct that requires planners to properly design it, as opposed to how human beings subjectively perceive and relate to it in their day-to-day experiences, as summarized by Kwan (Kwan 1999, Kwan and Weber 2003).

A large body of literature is devoted to various 'objective' approaches to measure accessibility. These approaches can be categorized roughly into four clusters (see Liu and Zhu 2004, Geurs and van Wee 2004):

(1) Opportunity-based measures such as the number of reachable destinations/locations/jobs within a certain distance/time/cost from a given origin (e.g. O'Sullivan *et al*. 2000, Witten *et al*. 2003, 2011, Martin *et al*. 2008, Benenson *et al*. 2011, Mavoa *et al*. 2012, Ferguson *et al*. 2013, Owen and Levinson 2015).
(2) Gravity-type or potential measures between locations (e.g. Minocha *et al*. 2008, Alam *et al*. 2010, Grengs *et al*. 2010).
(3) Utility-based/econometric measures such as the consumer surplus and net benefits derived by the individual users of the transportation system (e.g. Ben-Akiva and Lerman 1979).
(4) Space–time measures such as the range and frequency of activities in which a person can take part within given spatiotemporal constraints (e.g. Miller 1999, Neutens *et al*. 2010).

These approaches have further emphasized the importance of addressing the relative accessibility gaps between different modes, mainly public transit and private cars that reflect the severity of car dependence in urban areas (O'Sullivan *et al*. 2000, Martin *et al*. 2008, Tribby and Zandbergen 2012, Kaplan *et al*. 2014). A large number of studies have dwelled on mode-specific or relative accessibility measures: Blumenberg and Ong 2001, Hess 2005, Martin *et al*. 2008, Kawabata 2009, Grengs *et al*. 2010, Benenson *et al*. 2011, Mavoa *et al*. 2012, Ferguson *et al*. 2013, Mao and Nekorchuk 2013, Salonen and Toivonen 2013. Not surprisingly, most of the aforementioned studies often find significantly lower transit accessibility compared to the private car.

One non-trivial issue that arises from the review of previous studies is the definition of the spatial resolution for analysis. A main problem is lack of fit between these objective measures and the scale of human activity and travel decision-making: how to traverse the transport network comprised of different modes, lines and stops from a building at the point of origin to another building at the destination. Modeling this human-centered view of accessibility is not easy due to both data availability and computing limitations. Thus, the vast majority of previous studies measure accessibility aggregately at a rather coarse and granular scale of municipalities (Ivan *et al*. 2013); counties (Karner and Niemeier 2013), regular 1 km^2 grid (Papa and Bertolini 2015), neighborhoods (Witten *et al*. 2011), and, most often, at a scale of traffic analysis zones (TAZs) (Black and Conroy 1977, Shen 1998, Haas *et al*. 2008, Bhandari *et al*. 2009, Lao and Liu 2009, Grengs *et al*. 2010, Rashidi and Mohammadian 2011, Burkey 2012, Ferguson *et al*. 2013, Foth *et al*. 2013, Kaplan *et al*. 2014, Widener *et al*. 2015).

Typically, centroids of TAZs are assumed as the origin and destination points, leading to a common phenomenon of discontinuous estimates (or patchwork) when evaluating two adjacent zones. While a coarse spatial resolution may be sufficient for evaluating car-based accessibility (Nicolai and Nagel 2011), in the case of transit, the walk to and from a transit stop is an essential component of a trip. Disregarding of the walk time as well as the exact location of the transit stop may result in an uncontrolled as well as over- or underestimation of accessibility. Other components of transit accessibility, such as waiting time at transfers between stops when changing lines, are also averaged out in the calculations of transit accessibility that are based on aggregate spatial units. Use of data at resolutions higher than TAZ, such as zip codes (e.g. Owen and Levinson 2015), is quite rare and even then estimates are further aggregated for analysis purposes (e.g. Mavoa *et al*. 2012, Tribby and Zandbergen 2012, Salonen and Toivonen 2013, Welch 2013).

Spatially explicit high-resolution estimation of accessibility involves the processing of huge volumes of raw data and raises severe computational problems. This is possibly the reason most of the studies attempting to estimate accessibility at high resolution limit the size of the study area or the number of possible routes between origin and destination points in some way. Examples in the literature include studying a relatively small region within a metropolitan area (Kwan 1998, Lei and Church 2010, Welch 2013); modeling only a part of the population; analyzing only the catchment areas of transit stops (Kimpel *et al*. 2007); studying the location choices of particular families (Lee *et al*. 2009); examining only a sample of origin locations (Djurhuus *et al*. 2016); or concentrating on a limited number of destinations, within a small city with a limited number of transit lines (Lei and Church 2010).

The last two aforementioned studies are similar in approach to our study. They state the importance of realistic modeling of people's decisions when using transit modes that are based on the potential accessibility of location taking into account the return trip (Lei and Church 2010) or the availability of several transit stations within walking distance of the home (Kimpel *et al*. 2007, Djurhuus *et al*. 2016). However, they do not attempt to evaluate the advantage of high-resolution estimates of accessibility over those measures that are based on the aggregate view of the urban space and transit system.

A large metropolitan area with a population of 10 million contains 0.5–1 million buildings that may be all considered as origins and destinations, tens of thousands of street segments and hundreds of the transit lines (Benenson *et al*. 2010, 2011). For example, in the metropolitan area of Tel Aviv with a population of circa 3 million, there are about 250,000 buildings, 150,000 road segments, and over 300 bus lines. While existing tools commonly used by transportation planners, such as TRANSCAD or EMME, are in fact able to calculate transit accessibility at a zonal level, they were never designed for this purpose. Consequently, high-resolution calculation of accessibility with these common tools is extremely time-consuming and prohibitively expensive. The accuracy of transit accessibility estimates for the metropolitan area is thus essentially limited.

Recent developments in graph databases and algorithms (Kaliyar 2015) as well as the ability to use parallel computing (Crauser *et al*. 1998) offer disaggregated approaches to estimating transport accessibility. In this paper, we present a methodology for speedy calculations of accessibility, at the resolution of individual buildings, for the entire metropolitan area or parts of it. Our approach merges high-resolution urban GIS and an advanced graph database engine, and provides *precise estimates, in space and in time*, of transit-based accessibility to every location in the city for every hour of the day. The results of these calculations can be easily exported to any GIS software.

The rest of the paper is organized in the following manner. Section 2 presents the methodology we applied to estimate car and transit accessibility at a high spatial resolution of individual buildings. Section 3 presents the fundamentals of the computer application we developed. Section 4 shows the implementation of our approach using real data from the metropolitan area of Tel Aviv, comparing accessibility levels before and after the reform of the bus system carried out in 2011. Section 5 analyzes the resolution-related error in accessibility estimates at the building and zonal scales. Section 6 concludes and suggests future research directions.

2. Methodology

Typically, accessibility is a function of all three components of an urban system.

- Urban form/land use: the distribution of jobs and activities, and the socioeconomic characteristics of people;
- The transportation system: road and rail configurations, modes of travel, and the time and cost of travel between locations;
- Human travel-activity behavior: the benefits that individuals obtain from traveling to different destinations.

The transportation system slowly follows the changes in urban form and transport policy while individual travelers adapt to the changes in the transportation system. However, travelers' behavior is regarded as bounded-rational, and their responses to changes in the transportation system are hard to predict (Ben-Elia and Avineri 2015). As a consequence, we assume in our analysis that travelers' potential mobility reflects their experienced accessibility. We do not attempt to predict individual activity-travel decisions, but concentrate on evaluating the impacts of transportation changes on travelers' potential mobility given a fixed set of land use origins and destinations.

We measure potential accessibility by the accumulated value of a selected activity (e.g. number of jobs, places of leisure or commerce) a traveler can reach within a given time frame (as up to 30 min or an hour) using a specific transportation mode. We compare between accessibility using different transportation modes (car and transit) and estimate the ratio between them as relative accessibility. While we focus on accessibility with the private car and transit, bicycle and pedestrian movements can be estimated in the same way also. Our accessibility measures are based on the precise estimate of the *total potential travel time* between (O)rigin and (D)estination defined for a given transportation (M)ode at the resolution of a single building (as proposed by Benenson *et al*. 2011).

2.1 *Formal definitions*

Let us consider two modes, (B)us and private (C)ar:

2.1.1 *Total travel time by given modes*

- *Bus total travel time (BTT)*:

BTT = walk time from origin building to a stop of bus #1

+ Waiting time of bus #1
+ Travel time of bus #1
+ [Transfer walk time to bus #2 + waiting time of bus #2 + travel time of bus #2]
+ [Transfer component related to additional buses]
+ Walk time from the final stop to destination building.

Square brackets denote optional components.

- *Car total travel time (CTT)*:

CTT = walk time from origin building to the parking place

+ Car in vehicle time
+ Walk time from the final parking place to destination building.

Estimates of potential accessibility are based, as is common in the literature, on the notions of access and service areas.

2.1.2 *Access and service area*

- Let *MTT* denote a mode travel time and *S* denote the region of interest. We define the access and service areas for each mode: given origin building *O*, transportation mode *M,* and travel time τ, let us define *mode access area* – $MAA_O(\tau)$ – as the area of *S* containing all destination buildings *D* that can be reached from *O* with *M* during MTT $\leq \tau$ (Figure 1, left).
- Given destination building *D*, transportation mode *M,* and travel time τ, let us define *mode service area* – $MSA_D(\tau)$ – as the area of *S* containing all origin buildings *O* from which a given destination building *D* can be reached during MTT $\leq \tau$ (Figure 1, right).

In what follows, we consider bus and car access and service areas – BAA, CAA, BSA, and CSA.

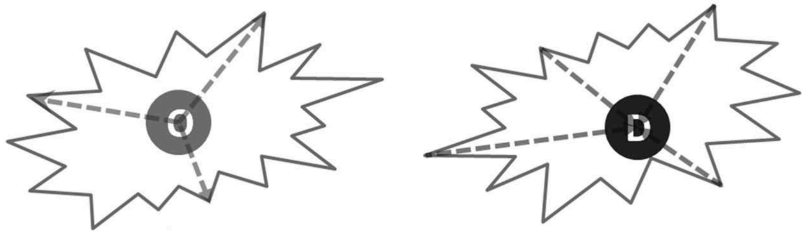

Figure 1. Schematic presentation of the access (left) and service (right) areas.

2.1.3 *Absolute potential accessibility*

Given an origin O and mode access area for this origin $MAA_O(\tau)$, or a destination D and its service area $MSA_D(\tau)$, the accessibility to any particular activity type k can be defined as

Mode M potential *access to* the destinations for activity k:

$$MPA_{O,}k(\tau) = \Sigma_D\{D_{k,\text{Capacity}}|D \in MAA_O(\tau)\}. \quad (1)$$

Mode M potential *accessibility from* the origins for activity k:

$$MPS_{D,}k(\tau) = \Sigma_O\{O_{k,\text{Capacity}}|O \in MSA_D(\tau)\}. \quad (2)$$

where $D_{k,\text{capacity}}/O_{k,\text{capacity}}$ are the capacities of destinations/origins for activity type k.

In what follows, we analyze potential accessibility by bus and car (using the above notation) to destinations from a given origin O: $BPA_{O,k}$ and $CPA_{O,k}$ and from origins to a given destination D: $BPS_{D,k}$ and $CPS_{D,k}$. We apply the analysis to investigate the potential accessibility to employment in Tel Aviv metropolitan area.

Examples of the activity types and their capacities can be the number of different kinds of jobs at destinations, the number of dwellings of a certain type, or the number of family members that are interested in a certain type of travel at origin buildings.

The accessibility estimates are sensitive to the choice of the region S. The closer a certain origin or destination is to the region's border, the higher is the potential bias of the estimate because destinations (in case of the access area) or origins (in case of the service area) that are located beyond the border are ignored. To reduce this bias, S should not disrupt a continuous pattern of destinations or origins, and always include these patterns as a whole, preferably with significant margins. In this respect, the estimating of access/service areas for an entire metropolitan area can be a good initial choice if external trips are not significantly large.

2.1.4 *Relative accessibility*

Different modes provide different levels of accessibility at similar times and travel durations. To analyze the gaps between modes' accessibility, we employ relative accessibility. As the private car usually provides better levels of accessibility throughout a metropolitan area, city residents using other transportation modes will usually assess them in comparison to the potential accessibility provided by the car. In this paper, we concentrate on comparing accessibility by car and by public transit.

Relative accessibility is calculated as the *ratio of absolute accessibilities* for a certain activity type k and travel time τ:

Given an origin building O, the bus *to* car *accessibility ratio* $AA^{\text{Bus:Car}}$ for the access areas is computed as[1]

$$AA^{\text{Bus:Car}}_{O,k}(\tau) = \text{BPA}_{O,k}(\tau)/\text{CPA}_{O,k}(\tau) \tag{3}$$

Given a destination building D, the bus *to* car *accessibility ratio* $SA^{\text{Bus:Car}}$ *for the service area* is

$$SA^{\text{Bus:Car}}_{D,k}(\tau) = \text{BPS}_{D,k}(\tau)/\text{CPS}_{D,k}(\tau) \tag{4}$$

3. Computer application

Our computer application implements mode-dependent calculations of access and service areas. Provided the required data is available, it estimates accessibility indices for origins or destinations of particular activity type k accounting for their capacities, using Equations (1)–(2) and (3)–(4).

3.1 *Inputs and outputs*

The necessary input database includes

- A layer of roads with the attributes sufficient for constructing a network.
- A layer of all transit modes: railroads, metros, light rail lines and buses with their stations and stops; each line is related to the links and junctions of the road network it passes. The stops of each line are related to a line.
- A table of transit departure and arrival times for each stop given as an exact time table or in terms of frequencies.
- Layer(s) of origin/destinations with capacities given: buildings, commercial facilities, offices and industry, parks and leisure. These layers enable estimating the accessibility to specific land uses and origins/destinations, by types and with respect to their capacities.

We used Google's General Transit Feeder Specification database for the metropolitan area of Tel Aviv, freely available from the Israeli Ministry of Transport, to obtain the updated data on transit lines, stops, and timetables.

Outputs include a series of tables of the accessibility indices for every spatial unit and corresponding aggregate tables and charts. To present accessibility maps, these tables are related to the GIS layers.

An accessibility map is defined by the travel start time in case of BPA and CPA or arrival time in case of BPS and CPS, and additional parameters as presented in Table 1.

3.2 *Generation of transit and car graphs*

We estimate accessibility based on the shortest path, by car or transit, between every OD pair. To do that, we translate the road (R) and transit (T) networks into directed graphs. The road network is translated into a road graph (RGraph) in a standard fashion:

Table 1. Basic parameters for accessibility analysis.

Parameter	Value
Max aerial walking distance between a trip origin and transit stop or between final stop of a transit trip and destination	400 m
Transit boarding time	07:15–07:30 AM
Transfers between lines	Yes
Max walking distance between transfer stops	200 m
Max waiting time at transfer stop	10 min
Max total trip time	45 min
Walking time from a trip origin to parking	0 min
Parking search and walk time at a trip destination	5 min
Average walking speed	1 m/s (3.6 km/h)
Average speed of an urban car trip	5 m/s (18 km/h)

junctions become nodes of an RGraph, street sections become links with two-way sections translated into two links, while one-way sections into one link, and travel time is translated into the link impedance.[2]

The construction of the transit network into a transit graph (TGraph) is less evident: given the lines, stops, and timetable, we define the nodes N of the TGraph by the quadruple:

$$N = < \text{T\_LINE\_ID, TERMINAL\_DEPARTURE\_TIME, STOP\_ID, STOP\_ARRIVAL\_TIME}>,$$

Two nodes N_1 and N_2 of a TGraph:

$$N_1 = < \text{T\_LINE\_ID}_1, \text{TERMINAL\_DEPARTURE\_TIME}_1, \text{STOP\_ID}_1, \text{STOP\_ARRIVAL\_TIME}_1>$$

and

$$N_2 = < \text{T\_LINE\_ID}_2, \text{TERMINAL\_DEPARTURE\_TIME}_2, \text{STOP\_ID}_2, \text{STOP\_ARRIVAL\_TIME}_2>$$

are connected by link L_{12} in two cases:

(1) The vehicle of the same transit line drives from STOP_ID_1 to STOP_ID_2:

$\text{T\_LINE\_ID}_1 = \text{T\_LINE\_ID}_2$,
$\text{TERMINAL\_DEPARTURE\_TIME}_1 = \text{TERMINAL\_DEPARTURE\_TIME}_2$ and
STOP_ID_2 is the next to STOP_ID_1 on the transit line T_LINE_ID_1.

The impedance of the link L_{12} is equal in this case to:

$\text{STOP\_ARRIVAL\_TIME}_2 - \text{STOP\_ARRIVAL\_TIME}_1$.

(2) A passenger can transfer between N_1 and N_2 – alight from the vehicle at STOP_ID_1 and board the other one at a stop STOP_ID_2:

A transfer can happen if the walk time W_{12} between STOP_ID_1 and STOP_ID_2 is less or equal to the maximal possible walk time $WALK_{max}$ and the time interval between lines arrivals at these stops is less than the walk time and maximal waiting time $WAIT_{max}$ at a stop:

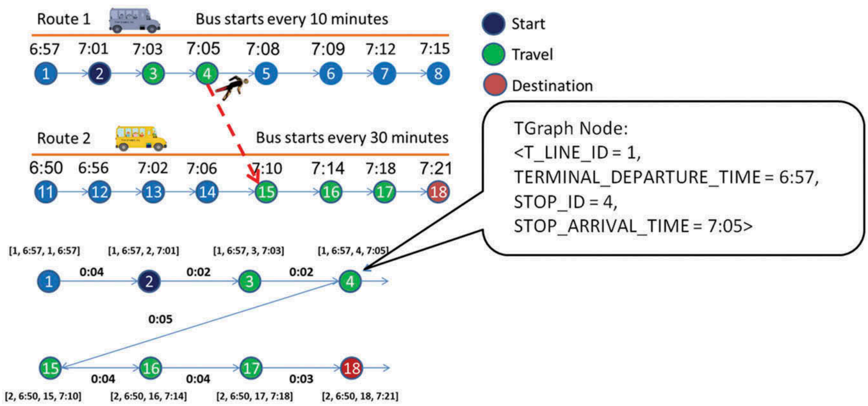

Figure 2. Representation of the transit trip as a path on a graph.

$$W_{12} \le WALK_{max} \text{ and } W_{12} \le STOP\_ARRIVAL\_TIME_2 - STOP\_ARRIVAL\_TIME_1 \le W_{12} + WAIT_{max.}$$

Figure 2 presents an example of the translation of a bus journey from origin to destination into a path on the TGraph.

To obtain the full RGraph and TGraph, we extend each of them to include nodes that represent buildings and links representing connections between the buildings and the road junctions in case of an RGraph or transit stops in case of a TGraph. In both cases, each building (B) is considered as a graph node (B-node). In the RGraph, a B-node and a node N representing the road junction are connected (by two links, B→N and N→B) if the walk time between B and N is less than W_{max}. The impedance of each of these two links is equal to a walk time between them.

In a TGraph, a B-node is connected to a T-node N,

$$N = < T\_LINE\_ID, TERMINAL\_DEPARTURE\_TIME, STOP\_ID, STOP\_ARRIVAL\_TIME>$$

if the walk time between B and N is less than $WALK_{max}$, and

$$T_{start} + WALK_{max} < STOP\_ARRIVAL\_TIME < T_{start} + WALK_{max} + WAIT_{max}$$

where T_{start} is the departure time of the traveler.

Unlike the case of an RGraph, in the TGraph the relation between the B-nodes and nodes representing transit stops is asymmetric: The only required condition for a T-node N to be connected to a B-node B is that the walk time between N and B is less than $WALK_{max}$.

The impedance of a link between the B-node and a node N of a TGraph is the walking time between B and N plus the waiting time for the arriving bus. The impedance of a link between a node N of the TGraph and B-node is just the walking time from a corresponding stop to the building.

Note that the definition of the TGraph nodes originating from stops also includes a temporal stamp (STOP_ARRIVAL_TIME). In this way, the TGraph incorporates the entire timetable. As a result, if constructed for the entire day, a TGraph is extremely large. For practical uses, TGraph is constructed for an investigated time interval, usually of 2 h duration.

Assuming that the travelers always choose the shortest path between two nodes, the representation of the transit and road networks as RGraph and TGraph enables the application of standard Dijkstra algorithms for building minimal spanning tree (Dijkstra 1959) that finds all the shortest paths, up to a certain accumulated impedance (travel time), between a given building and all other buildings and, in opposite direction, all shortest paths between buildings at a certain distance and a given building. In this way, the service and access areas for any given building are estimated. Calculation of the shortest paths between the nodes of the RGraph or TGraph that represent junctions or transit stops is implemented within the high-performance No-SQL Neo4J graph database (http://www.neo4j.org/). The rest of the calculations are performed with the SQL DBMS server. See more details in the Appendix.

The calculation of car accessibility for a given travel time (and period of the day) is conducted once and subsequently used as the denominator in all the rest of the calculations of relative accessibility according to Equations (3) and (4) and the accompanying parameters they depend on as described in Table 1. The numerator of Equations (3) and (4) depends on the transit time table that also varies during the day. With the graph-based computations, we can recalculate the numerator for a certain time period during a day in a manner of hours.

The output is a table of accessibility indices, at which every origin O or destination D building is characterized by the values of indices $\mathrm{MPA}_{O,k}(\tau)$ or $\mathrm{MPS}_{D,k}(\tau)$ for the given range of τ. In applications, we produce the tables of these indices at time resolution of 5 min for $\tau = 5, 10, \ldots,$ minutes of travel. For visualization, the tables of indices are joined to the shape file of Voronoi polygons that are constructed based on the buildings' centroids. Below, we present these maps for the values of τ = 15, 30, and 45 min.

4. Case study: accessibility impacts of the bus reform in Tel Aviv

We implement the proposed methodology and computer application to compare the changes in transit accessibility before and after the 2011 bus network reform. This reform changed many of the lines in the city and metropolitan area of Tel Aviv. Mainly, by adding new lines, cancelling lines, shortening and straitening lines, but without major changes to the locations of bus stops. We have chosen morning peak hours for analyzing the impact of the reform on accessibility by car and by bus (including the regional rail network) for all work trips (employment). In what follows, we consider travels that start at 07:15 whose origins are buildings within the municipal area of the city of Tel Aviv to any destination building in the greater metropolitan area. The results are presented in the maps below for number of jobs and for relative accessibility. The same analysis can be repeated for other periods of the day.

Figure 3 depicts absolute car morning accessibility to employment (the number of accessible jobs by car) in the entire Tel Aviv metropolitan area from every building within the city of Tel Aviv. This map serves as a basis (i.e. the denominator) for estimating relative accessibility both before and after the reform. The three maps depicted and Figures 4–9 further down are constructed for 15, 30, and 45 min trips. Figures 4 and 5 map the absolute

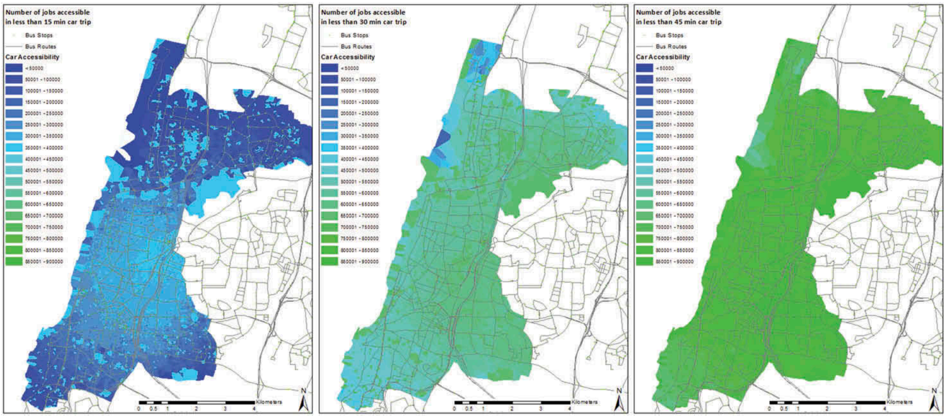

Figure 3. Accessibility to employment by car for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

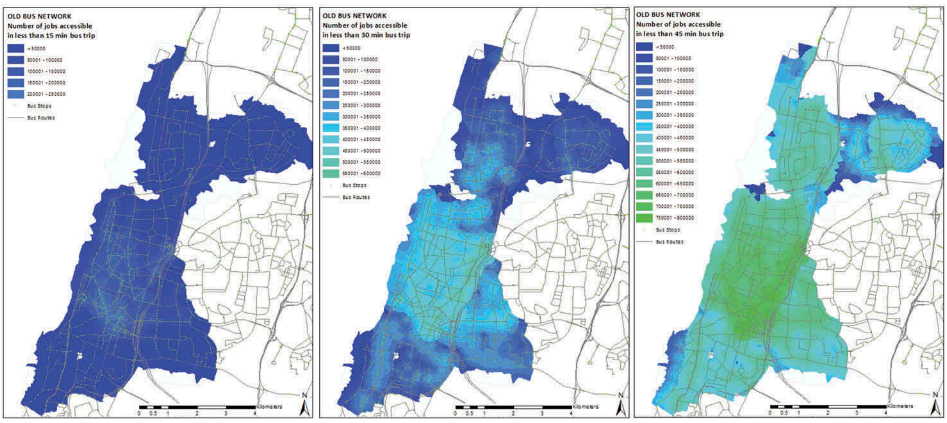

Figure 4. Accessibility to employment by bus, before the reform for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

transit morning accessibility to employment before and after the reform implementation. Figure 6 maps the average change in morning accessibility by bus after the reform, calculated as *100% * (accessibility, new network – accessibility, old network)/(accessibility, old network)*. There is, on average, an improvement for trips departing at 07:15 28.9%, 39.4%, and 39.0% for the 15, 30, and 45 min trips, respectively.

However, this improvement is not uniformly distributed across the city. We can see that for shorter trips there are areas in the city where accessibility to employment by bus actually decreased (red hue), mainly in older inner neighborhoods. In contrast, accessibility by bus improved (green hue) mainly in newer and/or peripheral neighborhoods that had lower accessibility before. For longer trips, this variation disappears except in the northeastern quarter of the city. We continue this analysis by examining relative accessibility estimates.

Figures 7 and 8 depict the relative accessibility (the ratio of jobs accessible by bus/ jobs accessible by car) before and after the reform, while Figure 9 presents the changes in relative accessibility in the morning achieved by the reform.

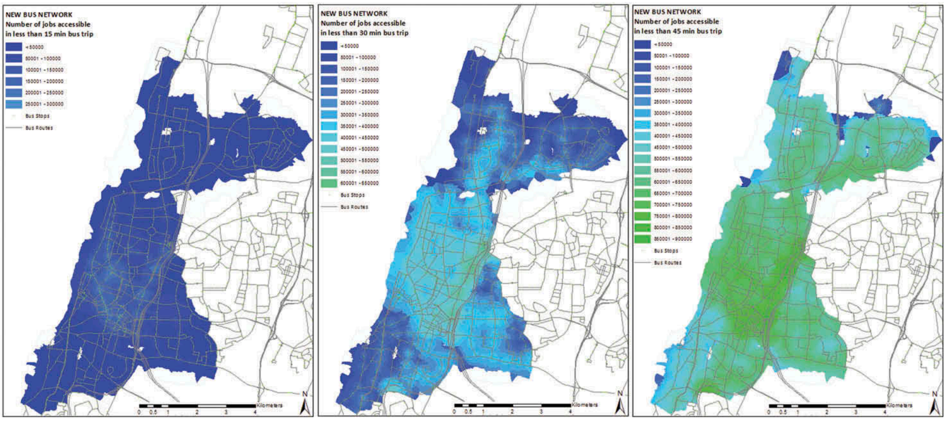

Figure 5. Accessibility to employment by bus, after the reform for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

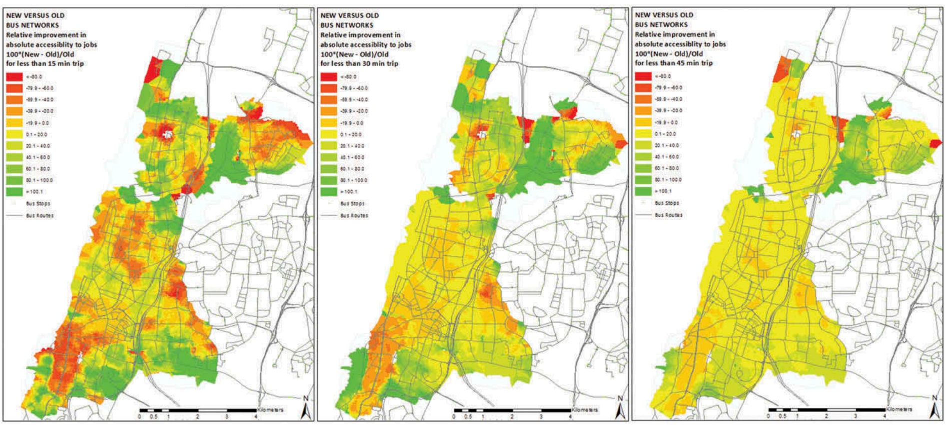

Figure 6. Relative improvement in absolute accessibility to employment by bus after the reform, calculated as 100% * (new – old)/old accessibility, for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

As we can see in Figure 9, the changes in relative accessibility in the morning are positive over the majority of the city. However, these benefits do not appear to be uniform across all the origins in the city, with some areas experiencing lower accessibility after the reform's implementation.

A final analysis is visible in Figure 10, where we present the percent change in relative accessibility after the reform versus relative accessibility before the reform for the same building. The trend curve is constructed applying local estimated scatterplot smoothing by Cleveland and Devlin (1988), a nonparametric regression that fits a regression curve based on subgroups of data points. The drawback of this method is the lack of a goodness-of-fit measure.

Clearly, there is an evident negative relation between the change in accessibility and its value before the reform. This implies that, on average, the higher the relative accessibility before the reform, the smaller is the percent change in accessibility after

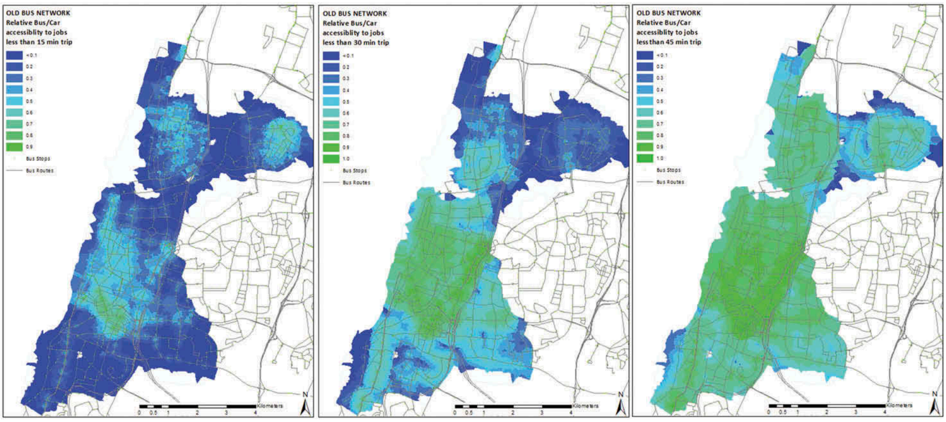

Figure 7. Relative accessibility to employment (bus/car), before the reform for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

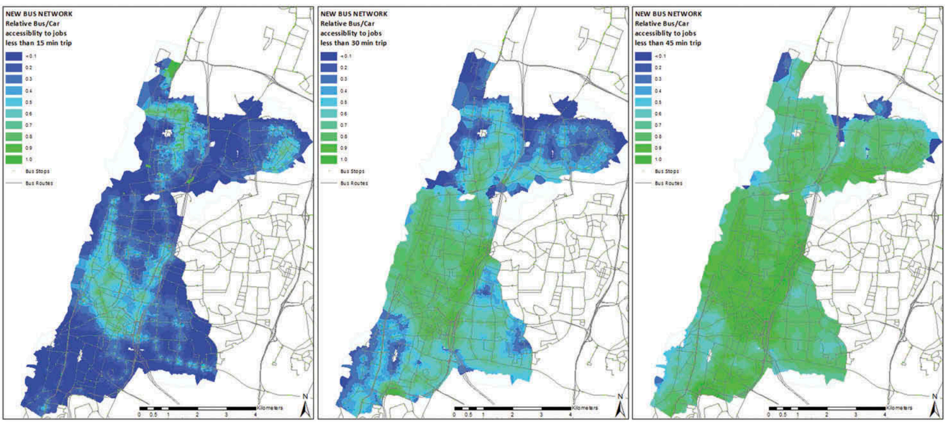

Figure 8. Relative accessibility to employment (bus/car), after the reform for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

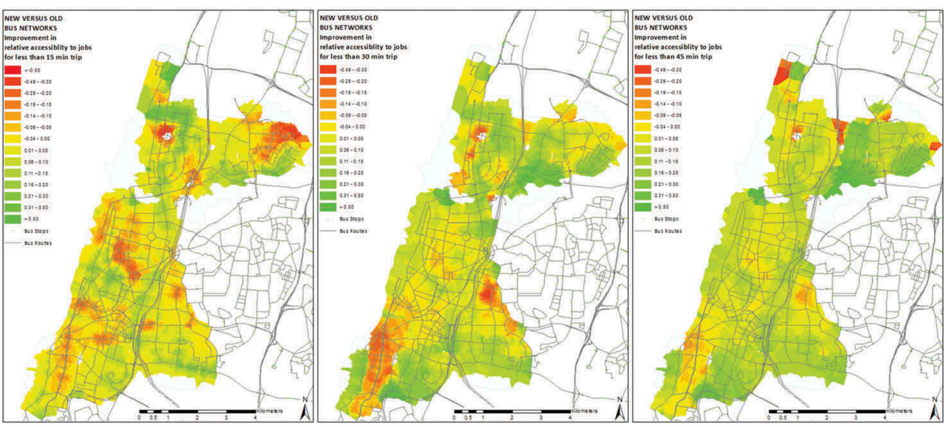

Figure 9. Reform changes in relative accessibility to employment for 15 (left), 30 (center), and 45 (right) min trips departing between 07:15 and 07:30.

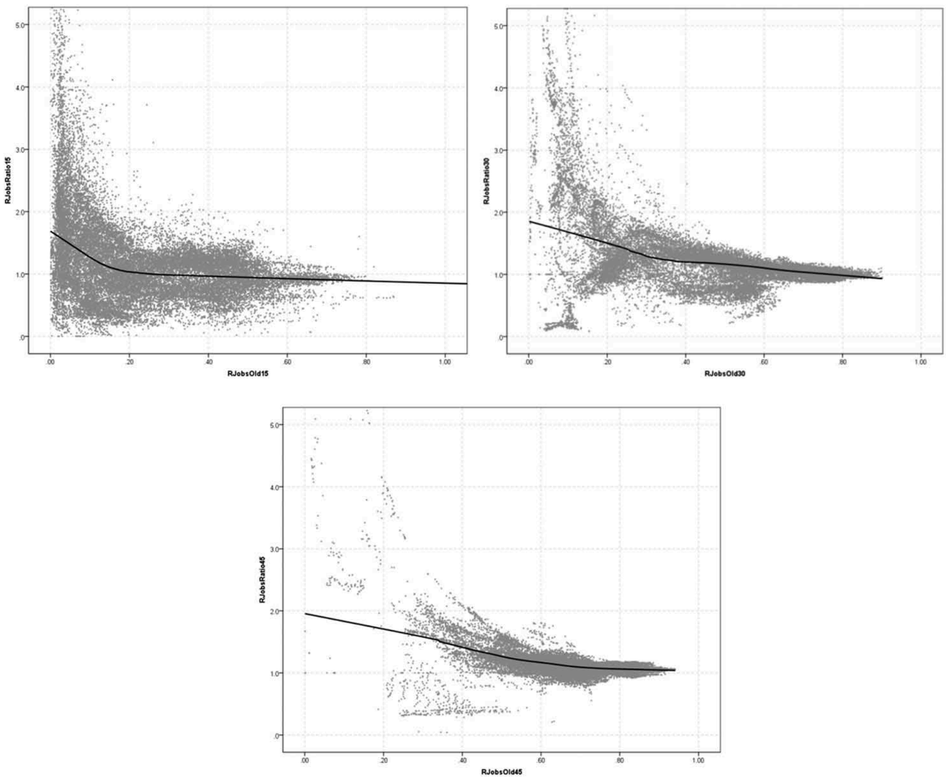

Figure 10. Ratio between percent change in relative accessibility after the reform and relative accessibility before the reform in the Tel Aviv metropolitan area for 15 (top left), 30 (top right), and 45 (bottom right) min trips departing between 07:15 and 07:30.

the reform. That is, the bus reform did, in fact, benefit those travelers that experienced low relative accessibility; however, as we demonstrated above, the benefits mainly accrue to longer trips and are not uniformly distributed across the city.

Overall, both absolute and relative accessibility in the morning have improved after the reform compared to their respective value before the reform. This is summarized in Table 2, which also shows the extent to which the overall changes due to the reform were more positive for the long trips compared to the shorter ones. The reason is that

Table 2. Aggregate statistics of relative accessibility to employment in the morning – no. of jobs in the entire Tel Aviv metropolitan area from every building within the city of Tel Aviv – before and after the bus reform for trip durations of 15, 30, and 45 min departing at 07:15.

Aggregate statistic	15 min	30 min	45 min
Average relative accessibility before the reform	0.233	0.480	0.664
Average relative accessibility after the reform	0.237	0.526	0.741
Average change in relative accessibility	0.004	0.046	0.077
STD of relative accessibility changes	0.096	0.102	0.086
Minimum of relative accessibility changes	−0.73	−0.40	−0.49
Maximum of relative accessibility changes	1.11	0.74	0.75
Fraction of the city area where the relative accessibility has improved	0.514	0.633	0.819
Fraction of the city population within the area of improved relative accessibility	0.533	0.654	0.825

the reform mainly modified the bus routes, but did not have much influence on timetables (except new lines) and the location of the stop. Therefore, for shorter trip durations, walking and waiting time did not change much due to the reform while their shares increase relatively more compared to the longer trips. As the majority of trips from inner city origins are within the city limits, it is likely that most trips are less than 45 min long.

5. Justification for a high-resolution analysis

Transportation planning is commonly bounded to TAZs and their characteristics as the basis of any analysis. This is mainly due to availability of the data and lack of high-end computation facilities. We argue that for evaluating transit accessibility correctly a view at much higher resolution is essential and justify this by high intra-variability of accessibility within the TAZ themselves, as can be seen in Figure 10. The reason is evident – walking and waiting time at the bus stops takes up a significant share of the total door-to-door trip duration by transit. Let us assume, for simplicity, that the walking speed is uniformly distributed in the population of travelers between 0.5 m/s (1.8 km/h) and 1.5 m/s (5.4 km/h) and account for 200 m as rough estimate of the sum of walk distances between the building and a bus stop in the beginning and end of a trip. The duration of walk varies, in this case, between 2.2 and 6.6 min, with an average walk time ≈ 3.6 min and STD ≈ 1.2 min. Accounting for the time of the entire trip, we can thus establish the TAZ '*homogeneity threshold*' in terms of the inter-TAZ coefficient of variation (CV), as CV ≅ 10%, 5%, and 3%, for trip durations of 15, 30, and 45 min, respectively. The variation in accessibility within the TAZ is important if it is above this level.

We apply the above view for recognizing areas with a similar level of accessibility. A priory, the walking time from each of two adjacent buildings to all transit stops is almost the same and, thus, accessibility estimates for these building should be very close. The further away are any two buildings, the higher may be the difference in accessibility. Following this logic, we can test whether the variation of accessibility within the TAZ areas is below the basic uncertainty and, thus, TAZ-based partition view is sufficient for transportation planning and assessment. Figure 11 presents the map of the CV values for the Tel Aviv TAZ partition, and Table 3 presents the fraction of TAZs for which the CV of accessibility is above the 'homogeneity threshold' and the total area and population of these TAZ.

As can be seen in the maps in Figure 11, for the majority of the TAZ the CV value is above the threshold values. Moreover, the decrease of the threshold with the increase in total trip time results in a steady fraction of these TAZ for trips of 30 min and longer. This implies that analysis at the zonal level will ignore that for many TAZ different travelers living there will experience different levels of accessibility by transit. The implication is that analysis at zonal resolution will not capture accurately enough the penalizing effects of walking and waiting time on transit ridership. The CV value is below the threshold for 30% of the Tel Aviv TAZ. Consequently, to improve the analysis of accessibility, the zonal partition of the city should be modified for 70% of the city's TAZ with a high level of internal accessibility. These TAZs should be subdivided into smaller ones. The estimation of building-level accessibility is thus critical for establishing

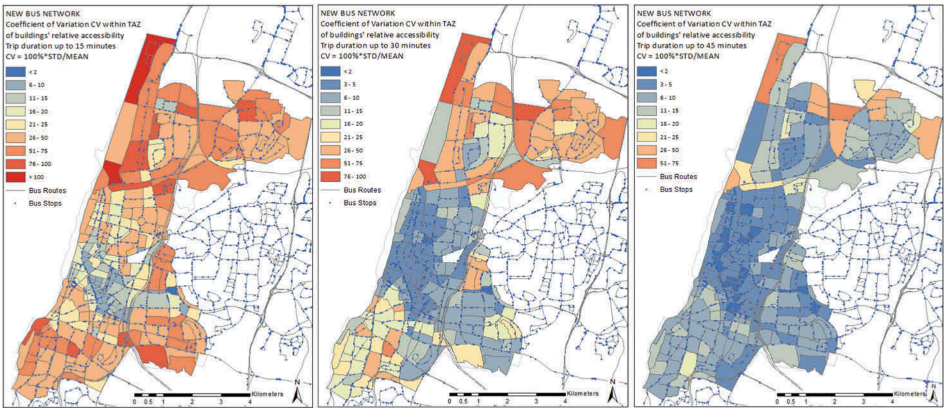

Figure 11. Coefficient of variation (CV = 100% * STD/mean) of the relative accessibility with the Tel Aviv transit system after the reform, over buildings within each TAZ for the trip of 15 (left), 30 (center), and 45 (right) min departing between 07:15 and 07:30.

Table 3. Tel Aviv TAZ zones for which the internal variation of accessibility is above the homogeneity threshold for trips departing at 07:15.

Duration of trip, in minutes	15 min	30 min	45 min
Fraction of TAZ with internal variation of accessibility above the homogeneity threshold	0.907	0.707	0.707
Fraction of the city area for these TAZ	0.955	0.865	0.826
Fraction of the total city population for these TAZ	0.959	0.775	0.779

the need for such a partition. We delay the presentation of a detailed partition methodology to a forthcoming paper.

It is important to note that out of approximately 1200 TAZ for the entire metropolitan area (population of ~2 million, area ~1500 km^2), more than half are the city of Tel Aviv (population ~400,000, area ~50 km^2). This suggests that Tel Aviv TAZs are much smaller than the TAZs outside Tel Aviv, and that the problem of interzonal variation would have been actually much worse if examining the entire region. This implies that accessibility estimates for transit trips in the entire metropolitan are most likely biased. High-resolution estimates of accessibility make it possible to assess the implications of this fact for transportation infrastructure investments and respective policy goals.

6. Conclusions and future work

In this paper, we presented a GIS method for analyzing accessibility at a spatial resolution of individual buildings. While the rationale behind our accessibility indicators is not new, the results demonstrate the importance of analyzing accessibility at a high resolution that serves as background for individuals' travel decisions and eventually mode choice. This resolution is very different from the common practice of transportation planners based on zones. The novel graph representation of transit travel and the combination of the very recent graph database with the traditional relational databases unify the view of travel for all modes and provide a comprehensive framework for our analysis. Implementation of the high-resolution approach requires substantial processing power that has recently become available and is improving all the time.

Our approach was implemented for investigating the recent bus reform in the metropolitan area of Tel Aviv. We analyzed the number of accessible jobs by transit (bus and rail) and the relative accessibility (transit vs. car) for work trips departing in the morning peak hour from origin buildings in the city of Tel Aviv to destinations in the entire metropolitan area. Our analysis shows that on average the bus reform improved the accessibility for these trips but not uniformly over the city's space. The high-resolution view enables analysis of the intrazonal variation of accessibility. We demonstrate that the aggregate analysis at the TAZ level may result in biased estimates, especially for short trips.

Future work includes several directions, some already in progress: first, to accomplish the proposed approach, in addition to analysis of the access areas performed in this paper, the analysis from the perspective of service areas will allow evaluation of how accessible are areas of interest such a hospitals, universities, transportation hubs, etc., from different areas. Based on the analysis of access and service areas, an analysis of the equity impacts of the bus reform has recently been carried out. We argue that a disaggregate analysis is better at distinguishing between areas served by the transit system and how they were influenced by the reform. Both aspects will be developed in a forthcoming publication.

Second, we estimate transit and car accessibility at the maximal possible resolution. Usually, this resolution can be decreased and the amount of calculation can be critically reduced – our analysis demonstrates that even some of the existing TAZs can be used as elementary units. In the same time, the majority of TAZs should be partitioned into smaller units that preserve sufficiently low internal variability of transit accessibility. Several approaches to subpartitioning can be proposed and such a subpartition can be suggested as a first step from the current TAZ-based to a high-resolution approach of transportation planning. The use of spatial units with a low internal variation of accessibility will be an important step toward transcending from macroscopic zone-based traffic and transit assignment models to unbiased meso- and microscopic agent-based multimodal simulation of traffic.

Third, while we examined the number of accessible locations for a given trip duration, these estimates do not relate directly to demand data. Demand data is commonly represented by OD matrices for different periods of the day, which represent the spatial and temporal spread of trips between different zones. Until detailed data on trip generation will become available (e.g. via mobile phone networks), we can disaggregate OD matrices and assign trip generation potential to each building relative to its floor area and use (residential, office, etc.). Our framework can then accommodate such data by transforming the indicators of potential accessibility and Equations (1)–(4) to passenger-hours or average trip times. OD estimates could be further improved by using smartcard data from transit ridership or mobile phone call data records (e.g. Trépanier *et al*. 2007, Calabrese *et al*. 2011). Note that our computations are based on planned travel times based on formal timetables. A likely advance is to extend the analysis to include real travel times based on actual arrival time at stops accounting for congestion. This would allow evaluating how large are accessibility gaps between planned and actual schedules. Another relevant point to note is that our analysis was conducted based on a 15 min period of departure time (07:15–07:30 AM) characteristic of the trips to work and is thus relevant for the part of the travelers' population only. Our approach could allow for wider departure intervals as well as for comparing the level of accessibility between several periods of time during the day.

Finally, the performance of the computational algorithm should be further improved. This will enable the test of uncertainty introduced by the current transportation planning approach, which results with transit line headways. Monte Carlo repetition with randomly established (but preserving headways) timetables will reveal the accessibility gaps in trips that include transfers. This analysis will allow investigating the accessibility impacts of future transportation development scenarios where precise timetables are not yet available.

Looking ahead, accessibility analysis should be combined with cost–benefit analysis of transportation infrastructure investments. Here, not only the efficiency gains (benefit–cost ratio) would be criteria for investment, but also the accessibility and equity impacts. This idea has been demonstrated for equity analysis (Gini index) at the TAZ level by Feng and Zhang (2012). We think that high-resolution Pareto-optimization view of the transportation infrastructure investments linking together transport efficiency, accessibility, and equity would allow a fuller examination of planning goals and projects' potential benefits to society and economy.

Notes

1. The use of relative accessibility partially reduces the influence of a boundary effect as the origins or destinations beyond the regional boundary will be excluded from the calculations for all modes (in (3)–(4) – both car and transit).
2. The RGraph for calculating bike accessibility is similar to the above, while link directions may be different (some links that are one way for the cars may become two directional for bikes) as well as links' impedance.

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Appendix: Application of relational database for accessibility calculation

To represent RGraph and TGraph, we apply the framework of relational database management system (RDBMS), the Microsoft SQL Server 2014 in our case. The RGraph and TGraph graphs are generated in Microsoft SQL Server and loaded into NO-SQL graph database Neo4j for applying Dijkstra spanning tree algorithm. The result is loaded back into the Microsoft SQL Server and stored SQL procedures are applied for further calculations. Below, we present the basic details of this process.

Let us, for convenience, use the identifiers (ID) of bus lines and stops as their names. Formally, a quadruple node

N1 = < PT_LINE_ID, TERMINAL_DEPARTURE_TIME, **STOP1_ID, STOP1_ARRIVAL_TIME**>
of the TGraph is connected, by the bus line PT_LINE_ID, to two nodes only –
N0 = < PT_LINE_ID, TERMINAL_DEPARTURE_TIME, **STOP0_ID, STOP0_ARRIVAL_TIME**>, and
N2 = < PT_LINE_ID, TERMINAL_DEPARTURE_TIME, **STOP2_ID, STOP2_ARRIVAL_TIME**>

where **STOP0_ID** is a stop that is previous to **STOP1_ID** on the PT_LINE_ID for the bus starting the travel at TERMINAL_DEPARTURE_TIME, and **STOP2_ID** is a stop next to **STOP1_ID** on the PT_LINE_ID for this bus.

Note that the degree of most of the quadruple nodes within the TGraph is exactly 2. That is, most of the quadruple nodes of the TGraph are connected, by just two (directed) links, to previous and next stops of the same PT vehicle traversing the same line. The degree of quadruple nodes at which transfers take place is higher than 2: in addition to being connected to quadruples denoting the previous and next stops of the line, this node is connected to the quadruples that can be reached by foot. The degree of most of the nodes of the RGraph is, evidently, 4.

In what follows, we use BuildingID for the identifier of the building B and NodeID for the identifier of the quadruple node N. Full RDBMS representation of the TGraph consists of four tables. We present them below as TableName (Meaning of field1, Meaning of field2, etc.):

- Building-TransitNode (BuildingID, trip start quadruple NodeID, walk time between building B and stop of the quadruple N + waiting time at a stop of quadruple N);
- DirectTransitTravel (quadruple NodeID, ID of the quadruple N that can be directly reached from the NodeID by the line of quadruple NodeID, travel time between stop of quadruple NodeID and stop of quadruple N);
- Transfer (NodeID of the stop of transfer start quadruple N1, NodeID of the stop of the transfer end quadruple N2, walk time between stops of N1 and N2 + waiting time at a stop of N2 for a line of quadruple N2);
- TransitNode-Building (trip final quadruple NodeID, BuildingID, walk time between the stop of the quadruple N and Building B).

	DirectPTTravel	
StartNode_ID	ArrivalNode_ID	TravelTime (min)
1	1	0
1	2	4
1	3	6
1	4	8
1	5	11
1	6	12
1	7	15
1	8	18
2	2	0
2	3	2
2	4	4
2	5	7
…	…	…
11	11	0
11	12	6
…	…	…
12	12	0
12	13	6
…	…	…

	Transfer	
StartNode_ID	ArrivalNode_ID	TransferTime (min)
4	15	5
…	…	…

The idea in our approach is expressed by the DirectTransitTravel one-to-many table: it presents all possible direct trips from a certain stop with a certain line. Standard SQL queries that join between this and other tables are sufficient for estimating access or service areas.

To illustrate the idea, we build the occurrences of DirectTransitTravel and Transfer tables for the example presented in Figure 1 (number in circle is used as quadruple's ID):

To understand the logic of querying: a 'Join' between DirectTransitTravel and Transfer tables provides trips from every stop to every transfer stop. A further join between the result and second copy of the DirectTransitTravel provide all trips between stops with zero or one transfer. The join between Building-TransitNode and the result above provides the trips between buildings and final stops of a trip and a further join with the TransitNode-Building finally provides trips between buildings. Most of the computation time is spent to the two last queries that include GroupBy clause as we need the minimal time travel between two buildings.

The output table contains three major fields: ID of the origin building, ID of the destination building, and total travel time. For further analysis, we also store the components of the trip time: walk times in the beginning and end of a trip and transfer time in case a trip includes transfer, bus travel time(s) and waiting times at the beginning of a trip and transfer.

Based on the output table, we construct the table that contains number of buildings, total population, and total number of jobs that can be accessed by car and by transit during a given trip time, usually at the time resolution of 5 min and up to 60 min. Relative accessibility is calculated as the ratio of the transit-based and car-based accessibility for each of the time periods. The resulting tables are further joined with the layer of buildings, thus enabling the map presentation of accessibility and, for convenience of presentation, with the level of Voronoi polygons that is built based on the buildings' centroids. These maps of relative and absolute accessibility are those presented in Section 4.

It is important to note that all four aforementioned tables are built based on the *exact timetables* of all lines and change whenever the timetable is changed. For the case of ~300 bus lines and several thousand stops in the Tel Aviv metropolitan area, the number of rows in the tables, for the bus trips that are less than 1 h, is about several million, within a standard range of modern SQL RDBMS abilities. As mentioned in the main text, calculation of the shortest paths between the nodes of the RGraph or TGraph that represent junctions or transit stops is implemented within the free version of the Neo4J graph database (http://www.neo4j.org/). The rest of the calculations were performed with the free version of the Microsoft SQL server. The total computation time for the full set of accessibility map for the Tel Aviv metropolitan area is about 2 h.

The calculation of accessibility is a very resource-consuming operation. For a typical metropolitan area of a Tel Aviv size, it requires significant amounts of CPU resources as well as disk storage. The software extracts data from GIS data sources and loads it into a relational database system, in our case Microsoft SQL Server 2014, that interacts with the Neo4J NO-SQL graph database. We make use of the advanced SQL queries, apply computing algorithms for huge data arrays that must strictly follow the predefined formats, and massively use parallelization and scaling techniques. With the properly established hardware, the resulting performance is sufficiently high and, as mentioned in the text of the papers, the calculation of accessibility maps presented in this paper takes several hours. However, it is highly possible that most of the readers will not be able to distinguish between the problems of data or hardware, especially when they happen in the middle of heavy calculations. Rather than opt for traditional open source, we therefore allow free run of the code on our server by any researcher as long as it is intentionally declared for scientific purposes.