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A spatially-explicit method for analyzing the equity of transit commuters' accessibility

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ABSTRACT

Equity is a critical dimension of accessibility assessment related to changes in transportation investments. We estimate equity based on a spatially-explicit computation of door to door travel times, in the metropolitan area, by car and by public transit at a resolution of individual buildings as origin and destination pairs. The Gini index and two new developed indices – the absolute and normalized accessibility loss are applied to evaluate the equity effects related to changes in the transit service. The method is tested in a case study of a recent bus line reform in the Metropolitan area of Tel Aviv highlighting areas where job accessibility by transit improved or declined. The implications of equity assessments for transportation planning and the assessment of infrastructure investments are further discussed.

1. Introduction

Accessibility has been a core concept in the understanding of the interrelationships between land use, transportation, and activity patterns for over 60 years (Hansen, 1959). Guaranteeing people's accessibility to markets and services is considered one of the most important goals of transportation planning and policy (Bristow et al., 2009). The layman's definition of accessibility is a person's ability to reach necessary or desired activities using the available transportation modes in an urban area (Geurs and Ritsema van Eck, 2001). Over the years various measures of accessibility have been suggested and implemented.

The literature considers roughly four approaches to the measurement of accessibility (see (Liu and Zhu, 2004; Geurs and van Wee, 2004 for a review): First, the simplest, is measuring the proximity between locations in time, distance or both (Alam et al., 2010; Grengs et al., 2010). Second, counting the cumulative number of reachable activities/opportunities/locations within a certain distance/time/cost threshold from a given origin. This can also be combined with a gravity-type model that supplies distance or time-defined weights for the opportunities. Numerous examples to this approach appear in the transport geography literature (Mavoa et al., 2012; O'Sullivan et al., 2000; Witten et al., 2011; Ferguson et al., 2013) and many others. Third, the econometrics literature suggests accessibility can be measured using utility-based approaches such as the net benefits derived by the individual users of the transportation system from reachable opportunities, evaluated through the log-sum in discrete choice models (Ben-Akiva and Lerman, 1979; Niemeier, 1997; De Jong et al., 2007). Fourth, time geography suggests accessibility is strongly related to capability, coupling and authority space-time constraints (Miller, 1999; Neutens et al., 2010; Järv et al., 2018).

As the measurement of accessibility is widely regarded as mode-specific, the literature has further considered measures of relative accessibility mainly between public transit and private cars (e.g. Benenson et al., 2011a, 2011b; Ferguson et al., 2013; Mavoa et al.,

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2012; Salonen and Toivonen, 2013; Yang et al., 2017; Tribby and Zandbergen, 2012; O'Sullivan et al., 2000). Unequivocally, these studies very often find significantly lower accessibility when measured for public transit users in comparison to car drivers.

A critical issue that influences the results of such accessibility measurements is the spatial scale applied. A human traveler with a known origin and destination (OD) will typically consider moving from one building at the point of origin to another building at the point of destination. Between these two points lies her choice set for mobility options and her decision how to traverse the transportation network comprised of different modes, lines and stops. Kwan (1999) thus asserts that accessibility perceived by human beings can be better understood with measures employed at the resolution of a single building, transit stop and at the temporal resolution of minutes. However, due to the excessive computational load for processing ODs at high resolution as well as lacking available population and activity/land use data, transportation planners have mainly worked with much larger spatial units - Transportation Analysis Zones (TAZ) that may include up to several thousand travelers and dozens of buildings. In contrast, within the territory of a large metropolitan area with a population of ten million there are say 0.5–1 million buildings of origins and destinations, thousands of stops and hundreds of transit lines compared to a few hundred TAZs (Benenson et al., 2011a, 2011b). For example, in the metropolitan area of Tel Aviv with a population of circa 3 million there are about 250,000 buildings, 3000 stops and over 300 bus lines but only about 1200 TAZs.

Unsurprisingly, the vast majority of studies measured accessibility aggregately at various spatial scales including (from larger to smaller): *counties* (Karner and Niemeier, 2013), municipalities (Ivan et al., 2013), *neighborhoods* (Witten et al., 2011), *census tracks* (Foth et al., 2013) *census block-groups* (Wang and Chen, 2015) and notably *TAZ's* (Shen, 1998; Kawabata and Shen, 2007; Ferguson et al., 2013; Burkey, 2012; Lao and Liu, 2009; Fransen et al., 2015; Zhou and Long, 2016; Tribby and Zandbergen, 2012; Ford et al., 2015; Ding and Zhou, 2015; Saghapour et al., 2016).

At these scales, and TAZ in particular, the zonal centroids are considered as the origin and destination points, leading to the well-known phenomenon of discontinuous estimates when evaluating accessibility between two adjacent zones. Benenson et al. (2017b) demonstrate the severity of this problem in the calculation of the relative accessibility between transit and car for the Tel Aviv metropolitan area. They calculate once at the TAZ scale and a second time at the building scale with aggregation to the TAZ scale. Both the estimated averages as well as the distribution come out very different (see in their Fig. 4 pp. 398). Evidently the "patchwork quilt" of discontinuous estimates is clearly visible at the TAZ scale but not so at the aggregate building scale that appears much smoother and continuous. Clearly it seems necessary to bridge this conceptual and methodological gap by establishing accessibility measurements that can directly match between the transportation planners' viewpoint and the spatial scale where humans make their activity-travel choices.

For the transit traveler the walk to and from stops as well as the waiting times including at line transfers and possibly travel fares (El-Geneidy et al., 2016) are all essential component of her door-to-door trip (Salonen and Toivonen, 2013; Manout et al., 2018). While possibly sufficient for evaluating car-based accessibility (Nicolai and Nagel, 2011) where the inter TAZ space is usually irrelevant given the speed in which motor vehicles travel, the scale of TAZ is likely too crude for correctly estimating transit accessibility and may well result in biased accessibility estimates. In fact Benenson et al. (2017a) analyze the coefficient of variation for the door-to-door travel time by transit in the city of Tel Aviv and find that in many cases inter-TAZ accessibility varies significantly. The reason is the wide differences in the mean out-of-vehicle times for different buildings within the same TAZ. The larger the TAZ the more acute is the problem and the distortion is especially problematic for short transit trips where the share of the out-of-vehicle time out of the total journey time is larger. These distortions never occur for car travel.

Although the standard commercial transportation planning packages, such as TransCAD, EMME and VISUM, are quite capable of calculating accessibility at the TAZ level, they were never intended for calculations at higher spatial resolutions that demand processing of huge volumes of raw data. This is why even the studies that estimate accessibility at higher resolutions try to limit the dimensions of the problem by decreasing the size of the study area to a small region within a larger metropolitan area (Kwan, 1998; Lei and Church, 2010; Welch, 2013); analyzing only the stops' catchment areas (Kimpel et al., 2007; Lee and Miller, 2018); location choices of particular households (Lee et al., 2009); a sample of origin locations (Djurhuus et al., 2015); or limiting the number of destinations (Lei and Church, 2010) or stops (Kiavash-Fayaz et al., 2017). A few recent studies have managed to break this methodological barrier and measured accessibility at spatial scales smaller than TAZ such as census blocks (Owen and Levinson, 2015; Cui and Levinson, 2018; Karner, 2018), multilevel grids (Chen et al., 2017) and cells (Liu et al., 2018). It seems Benenson et al. (2017a) were the first who succeeded in computing accessibility, at the resolution of individual buildings by merging high-resolution urban GIS and an advanced graph database engine while Cheng et al. (2018) have recently followed in their footsteps.

The issue of incorrect accessibility estimates filtrates to another directly related problem that has occupied transportation planners and the relevant accessibility analysis literature - namely that of accessibility equity. Equity relates to the questions who benefits and who loses out from decisions on transportation infrastructure and transit service investments and what is the distribution of these benefits and their burdens across society (Kwok and Yeh, 2004; Feitelson, 2002; Martens, 2012; Lucas, 2012; Lucas et al., 2016 and see the special issue of review papers edited by Di Ciommo and Shiftan (2017). In particular, there has been renewed interest in the equity of public transit provision (Welch and Mishra, 2013; Feng and Zhang, 2012; Pangbourne and Anable, 2011; Levinson, 2010; Wei et al., 2017; Monzón et al., 2013). The general view is that transportation investments should not only increase the average accessibility levels over the urban space, but also benefit dependent and underserviced groups, reducing the level of accessibility inequality in the metropolitan area (van Wee and Geurs, 2011; Martens et al., 2012).

The literature commonly differentiates between horizontal and vertical equity (Le Grand, 1984; Litman, 2002). These reflect two contrasting and complementary perspectives of transportation planning. The *horizontal equity* framework aims at fairly or equally distributing mobility services to the maximum number of travelers regardless of need or ability and encapsulates the "mass transit" perspective (Delbosc and Curry, 2011; Dadashpoor and Rostami, 2017). Conversely the *vertical equity* perspective follows the idea of social justice (Betts, 2007). It aims to provide accessibility according to specific abilities to those with the greatest "mobility need" (Currie, 2004) e.g. disabled travelers, or those without access to cars, or to specific demographic groups such as low-income, youth, elderly, or minorities (Ward, 2005; Garrett and Taylor, 1999; Deakin, 2007; Taylor et al., 2009; Fransen et al., 2015; Manaugh et al., 2015; Martínez et al., 2017; Murray and Davis, 2001). Several recent studies have aimed to measure transit accessibility equity applying various indices (Ricciardi et al., 2015; Griffin and Sener, 2016; Mortazavi, and Akbarzadeh, 2017; Jang et al., 2017; Pereira, 2018). Several studies have also attempted to bridge the important gap between accessibility and equity not only of ex-post analysis of the existing transit system for possibly operational improvements, but of ex-ante transit network design that ensures accessibility equity in the planning stage (Caggiani et al., 2017; Camporeale et al., 2017; Ruiz et al., 2017; Behbahani et al., 2018).

While there have been many studies involving transit accessibility equity most of them are still based on rather coarse spatial analysis notably TAZ. Accordingly the motivation and aim of this paper is to merge between the high spatial resolution computations of accessibility and the co-related assessment of equity. This is done by applying the spatially-explicit tool established by Benenson et al. (2017a) for computing accessibility and estimating the derived equity. We estimate equity using the well-known Gini index (Gini, 1912) and also develop two new indicators for estimating the absolute and normalized accessibly loss of transit travelers. These two are easily plotted on maps allowing to visually compare accessibility losses across the urban space. We test our method by examining the equity impacts for commuting to work during the morning peak hour, related to a case study of the changes in transit accessibility brought about by a recent bus network reform that had taken place in the metropolitan area of Tel Aviv, Israel in 2011.

The rest of the paper is organized in the following manner. Section 2 presents the methodology applied to compute accessibility at a high spatial resolution of individual buildings. Section 3 describes the equity indicators we applied and developed on the approach described in Section 2. Section 4 presents the case study results and the comparison of equity before and after the aforementioned bus reform. Section 5 presents a discussion, conclusions and future research directions.

2. Accessibility computation

The high-resolution spatially-explicit approach for estimating accessibility is fully described in our previous paper - Benenson et al. (2017a). Here we only repeat the important aspects. Estimates of accessibility are based on the computation of a modal-based shortest path (total door-to-door travel time for each mode) between every OD pair at the resolution of a single building while the road and transit networks are translated into directed graphs as proposed by Buerli (2012) and Benenson et al. (2011a, 2011b).

Basically we consider two modes only: (P)ublic Transit and (C)ar. Accordingly the total travel time by public transit is equal to (Square brackets denote optional components):

> Walk time from origin building to a stop of Line #1 + Waiting time of Line #1 + Travel time of Line #1 + [Transfer walk time to Line #2 + Waiting time of Line #2 + Travel time of Line #2] + [Transfer component related to additional lines] + Walk time from the final stop to destination building.

The total travel time by car (CTT) is computed as:

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

We calculate the potential accessibility as a cumulative opportunities measure of access and service areas with travel time threshold τ. Let MTT denote Mode Travel Time and S denote the planning region:

– Access area: Given origin building O, transportation mode M and travel time τ, define *Mode Access Area* - $MA_O(\tau)$ - as the part of S containing all destination buildings D that can be reached from O by mode M during MTT $\le \tau$.
– Service area: Given destination building D, transportation mode M and travel time τ, let us define *Mode Service Area* – $MS_D(\tau)$ - as the part of S containing all origin buildings O from which a given destination building D can be reached by mode M during MTT $\le \tau$.

Given an origin O and its access area $MA_O(\tau)$ or a destination D and its service area $MS_D(\tau)$, the potential accessibility can be defined as the total number of opportunities/activities in accessible destinations for a certain activity using Mode M. By "capacity for activity" we refer to the number of activities that can be performed in each building. In case of the access area, we define the potential accessibility from origin O to all the destinations that can be reached during the time τ or shorter as:

$$MPA_O(\tau) = \sum_D \{D_{CapacityForActivity} \mid D \in MA_O(\tau)\} \tag{1}$$

While in case of service area, we define the potential accessibility of destination D from all the origins, from which D can be reached during time τ or shorter, as:

$$MPS_D(\tau) = \sum_D \{O_{CapacityForActivity} \mid O \in MS_D(\tau)\} \tag{2}$$

where $D_{CapacityForActivity}$ and $O_{CapacityForActivity}$ are the capacities of destinations/origins for given activity type.

Travelers' perceptions of accessibility by public transit are based on the change in its potential accessibility provided relative to the accessibility by car. The latter is usually perceived as having a higher accessibility. That is, in most of the metropolitan areas – even those with extremely developed transit networks, car travel is still likely more efficient than using transit because of the direct connectivity and lack of transfers involved. The notion that transit provides poorer accessibility is not based on any normative stance on our part. We therefore compute *Relative Accessibility* as the *ratio of modal potential accessibilities*.

The public transit to car potential accessibility ratio given an origin building O, for access areas is:

$$APR_O(\tau) = PPA_O(\tau)/CPA_O(\tau) \tag{3}$$

and given a destination building D, *for service areas* the ratio is

$$SPR_D(\tau) = PPS_D(\tau)/CPS_D(\tau) \tag{4}$$

and assume that all measures are applied to a population group involved in a certain travel activity, such as commuting to work or participating in commercial activities.

Note, that the potential accessibility measures are computed for a certain population group traveling to a certain activity (e.g. commuting to work) from a single origin or to a single destination. However, when aggregate estimates are necessary in terms of population groups or activities or spatial units they can be summed up or averaged as will be shown below.

3. Equity indicators

Equity is a measure of the degree of variation of a certain attribute in the population e.g. income. The more equal is the distribution, the higher is the level of equity in society. Two well-known equity indicators are the Lorenz curve (Lorenz, 1905) and corresponding Gini index (Gini, 1912). Both measures are commonly used in economics as well as in a wide range of disciplines, including transportation and especially accessibility analysis (Fridstrom et al., 2001; Delbosc and Curry, 2011; Kaplan et al., 2014; Welch and Mishra, 2013 Thomopoulos and Grant-Muller, 2013; Jang et al., 2017; Ricciardi et al., 2015; Guzman et al., 2017; Xia et al., 2016). The Lorenz Curve (Fig. 1) is a graphical representation across the population of the cumulative distribution function of wealth and can be applied to any population attribute The Gini index is a measure of statistical dispersion that reflects the inequality in distribution of an attribute. For an ordered sample *S* of the population attribute y of a size *n*, $y_1 \le y_2 \le \dots \le y_i < y_{i+1} \le \dots \le y_{n-1} \le y_n$, the Gini index is computed as:

$$Gini(S) = 1 - \frac{2}{n-1}\left(n - \frac{\sum_{i=1}^{n} iy_i}{\sum_{i=1}^{n} y_i}\right) \tag{5}$$

Graphically, the Gini index is a ratio of the area locked between the line of equality and the Lorenz curve divided by the total area under the line of equality, or A/(A + B) in Fig. 1. The Gini index is always between 0 and 1. A value of 0 implies complete equality (each population member has the same value of an attribute y, whereas a value of 1 suggests complete inequality (one member has all). The lower is the Gini index, the more equal is the distribution of characteristic y in a sample S. Applied to accessibility the Lorenz curve and Gini index capture the difference between different modes and different networks.

However, the problem arises when two accessibility distributions have similar equity, but the averages are different as the Gini index is invariant to scale of attribute y. As such, the Gini index should always be examined together with the average accessibility. Based on average accessibility in terms of access area $MPA_O(\tau)$ or service area $MPS_D(\tau)$, we define the *Traveler's Accessibility Loss* when using public transit (P) instead of car (C) as the difference between their potential accessibilities for the same time threshold τ

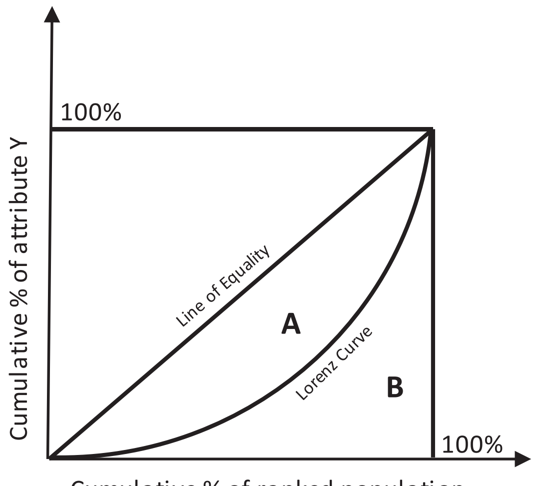

Fig. 1. Hypothetical depiction of the Lorenz curve for attribute Y. The Gini index Gini (S) is calculated as the ratio between the areas - A/(A + B).

i.e. $CPA_O(\tau) - PPA_O(\tau)$, for access area or $CPS_D(\tau) - PPS_D(\tau)$, for service areas. A somewhat similar approach for computing modal accessibility gaps is also presented by Palmateer and Levinson (2018) who refer to the term net person-weighted accessibility.

Given an area's partition into spatial units U_i, we define, within each unit, the *Absolute Accessibility Loss*: Let the total population of travelers in the unit be G_i, the number of public transit users $G_{i,P}$ and the number of users whose travel time by bus is τ or less be $G_{i,P}(\tau)$. Let the population of travelers of the entire area be G and the total number of transit users there be G_P. The *Unit's Absolute Accessibility Loss* is a product of$G_{i,P}(\tau)$ and *the* transit *Traveler's Absolute Accessibility Loss* during the same time τ. we denote this measure as $L_{i,O}(\tau)$ for the users' access and $L_D(\tau)$ for service areas.

$$L_{i,O}(\tau) = G_{i,P}(\tau)(CPA_O(\tau) - PPA_O(\tau)) \tag{6}$$

$$L_{i,D}(\tau) = G_{i,P}(\tau)(CPS_D(\tau) - PPS_D(\tau)) \tag{7}$$

Index L measures the *Absolute Loss of Accessibility* related to the use of public transit instead of car during a trip of duration τ by unit's population. It allows comparison, for example, between the outcomes of essential transit improvement that is available only to a few travelers and a minor transit improvement that is available to many travelers. If all unit travelers use cars - $G_{i,P} = 0$, or if potential accessibility by car and transit are the same, as $CPA_O(\tau) = PPA_O(\tau)$, then $L = 0$. If the majority of group members use transit or accessibility by car is essentially higher than accessibility by transit then L is high.

The L-index is not scalable and varies with the total size of travelers' population G_i in a spatial unit i that consists of car users $G_{i,C}$ and transit users $G_{i,P}$, $G_i = G_{i,C} + G_{i,P}$. We normalize L relative to the entire population of the unit and introduce the ***Normalized Accessibility Loss*** $\mathrm{N}(\tau)$

$$N_{i,O}(\tau) = G_{i,P}(\tau)(CPA_O(\tau) - PPA_O(\tau))/(G_i(\tau) *CPA_O(\tau)) \tag{8}$$

$$N_{i,D}(\tau) = G_{i,P}(\tau)(CPA_D(\tau) - PPA_D(\tau))/(G_i(\tau) *CPA_D(\tau)) \tag{9}$$

where $G_{i,P}(\tau)/G_i(\tau)$is the transit use share (e.g. estimated from the mode choice model, in the case of horizontal equity assessment or from a needs-based index, in case of a vertical equity assessment). Similar to L, $N = 0$ (i.e. no loss) if there are either no transit users ($G_{i,P} = \varnothing$}, or accessibilities by car and transit are essentially equal. If the entire population uses transit ($G_{i,P} = G_i$) then N is close to $1 - PPA_O(\tau)/CPA_O(\tau)$ for access areas or $1 - PPS_O(\tau)/CPS_O(\tau)$ for service areas. The values of L and N are calculated for spatial partition units at any level of resolution - from individual buildings up to the entire metropolitan area and then computed for any population or activity or population groups

The advantages of all these indexes are straightforward as: they allow creating both horizontal equity comparisons across all or some travelers as well as vertical equity comparisons along spatial and non-spatial categories (e.g. neighborhoods or socially excluded groups). The indices can accommodate any change in the transportation system and can be applied to any accessibility measure. However, some limitations should be noted including: over-simplicity in how accessibility is assessed and the need to have external knowledge on transit demand. Each of the above indices varies by hours of a day as frequencies and timetables change and in case the members of the investigated group travel in different hours of the day, this will result in different index outcomes for different periods of the day. To incorporate daily variation of travel into the final equity calculations weighted averages for different hours of the day can be used, where the weight reflects the relative activity of the group members at certain hours of the day. Different traffic conditions or preemptions may also result in different travel times between the same Origin (O) and Destination (D) and additional weighting over the traffic conditions may have to be applied. In addition irrespective of the traffic conditions, transit passengers are commonly unsure about arrival times or unaware of a timetable and, thus arrive at the boarding stop in advance, or risk being late. Travel time/cost uncertainty caused by recurring congestion, non-recurring delays, etc., can be simulated using Monte Carlo procedures for estimating the distribution of the OD travel time/cost for each OD-pair. Nonetheless, a high-resolution view of accessibility will demand high-performance computing to account for all these types of variations.

4. Case study

We now implement the proposed equity indices to compare the changes in the equity of public transit accessibility before and after the 2011 Tel Aviv transit network reform. This reform changed many of the bus lines in the city and metropolitan area of Tel Aviv, but without major changes in the locations of bus stops. We chose the morning peak hour for analyzing the impact of the reform on all commuting to work trips. Naturally, a full assessment of the bus reform should include additional time windows as well as other mandatory and none mandatory activities.

For the sake of brevity, we only consider access trips that start between 07:15 and 07:30 within the core metropolitan city of Tel Aviv (400 K population, 39 K buildings) with all possible destinations within the greater metropolitan area[1]. We have exploited the GIS layers of buildings (with the attributive data on the use of every building) and roads provided for this research by the Survey of Israel. The layer of TAZ with the data on population and number of jobs for each were provided for this research by NTA LTD. The OD matrix of trips in the Tel Aviv Metropolitan Area for the morning peak hours was provided by Ayalon Highways Co. LTD. To estimate the number of jobs we disaggregated the overall number of jobs in each TAZ over the buildings for "industrial" and "commercial" uses based on their relative floor area.

[1] Due to limitations of existing hardware we were not able to analyse the full scope of the Metropolitan area but opted to focus on the accessibility of the entire metropolitan from the core city area instead.

Table 1
Assumptions applied in the shortest path calculations.

Description	Value
Shortest transit path	
Max. walking distance to boarding stop/from alighting stop	400 m
Max walking distance between transfer stops	200 m
Walking speed	1 m/s = 3.6 km/h
Max wait time at stop	10 min
Max trip duration (door-to-door)	45 min
Shortest car path	
Average walking distance from parking to destination	2.5 min
Mean car speed	5 m/s = 18 km/h

Data on transit lines, stops and timetables were obtained from the GTFS (General Transit Feeder Specification) dataset for the non-holiday period of 2014. Additional assumptions applied in the shortest transit and car paths computations are presented in Table 1:

In what follows, we present accessibility and equity maps and tables that are relevant to this study only. We noted that the calculations for one set of initial conditions take about 14 h to complete using an Intel i7 machine with 64 GB memory.

Fig. 2 shows the changes in the relative accessibility transit/car (i.e. the potential accessibility ratio of the access areas - $APR_O(\tau)$) of residents of every building in the city of Tel Aviv to all jobs in the Metropolitan area during the morning peak for commuting durations of 15′, 30′ and 45′ (min); and calculated as:

$$(APR_O(\tau),\ \ new\ \ network - APR_O(\tau),\ \ old\ \ network)/(APR_O(\tau),\ \ old\ \ network) \tag{10}$$

Overall Relative accessibility improved after the reform. However, according to Benenson et al. (2017a), this improvement was not uniformly distributed across the city space. For trips of 15′, the accessibility to jobs by transit decreased or remained the same over 49% of areas in the city (red and dark yellow hue), mainly in older inner neighborhoods but improved (green hue, 51%) mainly in newer and or peripheral neighborhoods that had lower accessibility in the old network. The average change of accessibility is positive, but very low (0.004) that is, less than 2% of the average relative accessibility with the old transit network (see Table 2). The longer the trip, the higher is the improvement provided by the new transit network. For trips of 45′ the average improvement in relative accessibility is about 12% and accessibility improved in over 82% of the city area.

Fig. 3 presents the Lorenz curve and corresponding Gini indexes before and after the bus reform for the relative accessibility depicted in Fig. 1. The results suggest that the accessibility distribution after the reform is more equitable for the longer trips, while it does not change muchfor the shorter trips. The likely reason is that the reform mainly modified bus routes but did not have much influence on timetables and stop locations and, thus, walking and waiting time did not change much.

To estimate the Absolute and Normalized Accessibility Loss we use the morning peak demand for transit ($G_{i,P}$) and car ($G_{i,C}$) from the OD-matrices of the Tel Aviv Metropolitan Transportation Model. This model represents transit and car flows between 1249 TAZs. To enable the calculations at the resolution of single buildings we disaagregate the OD flows between TAZ to the flows between buildings, proportionally to the buildings' floor area (the layer of buildings was supplied by the Survey of Israel). Based on the

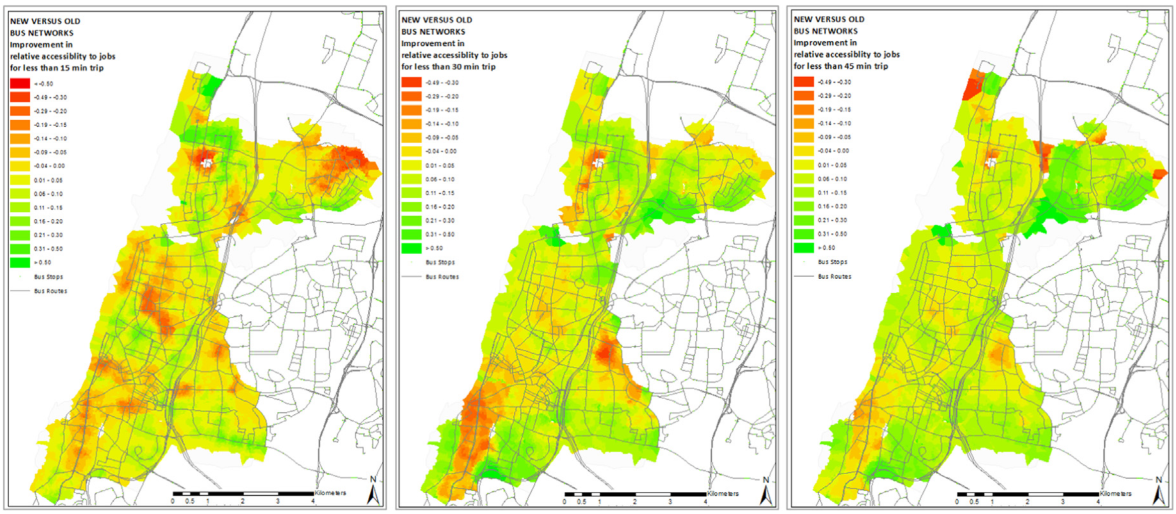

Fig. 2. Change in relative accessibility to jobs transit/car at resolution of buildings, after the reform for trips of 15′ (left), 30′ (center), 45′ (right) departing at 07:15, calculated as (New Relative Accessibility – Old Relative Accessibility)/Old Relative Accessibility.
Source Benenson et al., 2017a.

Table 2
Aggregate statistics of relative accessibility with the old and new transit networks.

Aggregate statistic	15′	30′	45′
Average absolute transit accessibility (thousands of accessible jobs) before the reform	56.6	268.4	532.6
Average absolute transit accessibility (thousands of accessible jobs) after the reform	56.4	292.8	594.4
Average absolute car accessibility (thousands of accessible jobs)	220.1	562.1	805.9
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

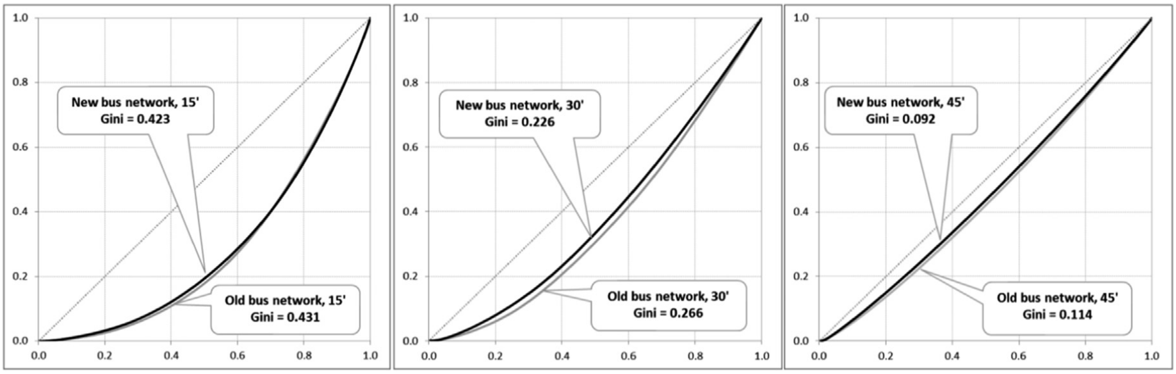

Fig. 3. Lorenz curves and Gini indexes computed for relative transit/car access areas from all the origin buildings within the city of Tel Aviv to all jobs in the entire Metropolitan area for trips of 15′, 30′ and 45′ departing between 07:15 and 7:30.

building attributes - footprint area and height - we calculated the floor area for each building assuming that the average height of a floor is 3 m as:

$$[\text{Building floor area}] = [\text{Area of building footprint}] * [\text{Building height}]/3 \quad (11)$$

The number of trips between any TAZ OD was disaggregated into the number of trips between pairs of buildings proportionally to the fractions of the floor areas of two buildings among the total floor areas of each TAZ. In this way, the OD matrix at the resolution of buildings was obtained and accessibility loss for every origin building in Tel-Aviv was calculated. Finally, the obtained accessibility estimates were aggregated by TAZ.

Fig. 3 presents the maps of Absolute Accessibility Loss $L_{i,O}$in terms of a 15′, 30′ and 45′ access area at TAZ level, for the old and new transit networks of Tel-Aviv, calculated as:

$$100\% * (L_{i,O}(\tau),\ \ new\ \ network - L_{i,O}(\tau), old\ \ network)/(L_{i,O}(\tau),\ \ old\ \ network) \quad (12)$$

As already noted, the longer the trip the more pronounced are the absolute accessibility losses or gains. Fig. 4 shows the difference by TAZ - where these losses were reduced or increased. Table 3 presents aggregate statistics for absolute accessibility loss. According to Fig. 4, accessibility loss decreased over 89% of Tel-Aviv area. Green hues indicating a decrease in the absolute loss that are more pronounced in the peripheral neighborhoods in the North-Eastern and South-Eastern parts of the city (circles), while brown in the South-West of the city (rounded rectangles) indicate an increase in the absolute loss.

The results suggest that the reduction in the absolute accessibility loss for transit users is mainly attributed to the longer trip durations, while for the trips of short and average duration, there are areas where the accessibility losses of the transit users have increased after the reform. This is due to the nature of the reform that took lines from inner streets and moved them to main thoroughfares. Overall this result resembles very closely the picture seen in Fig. 2 for the relative accessibility.

Table 4 presents the statistics and Fig. 5 presents the maps of the Normalized Accessibility Loss in terms of access area $N_{i,O}$ for the old and new transit networks of Tel-Aviv, during the morning peak:

$$(N_{i,O}(\tau),\ \ new\ \ network - N_{i,O}(\tau), old\ \ network)/(N_{i,O}(\tau), old\ \ network) \quad (13)$$

As can be expected based on the map of absolute accessibility loss (Fig. 4), the main areas where N decreased is the North-Eastern and South-Eastern quadrants of the city.

The results in Table 4 show a similar picture to the one seen for the absolute loss; namely that overall the reform did reduce the normalized loss whilst this reduction is mainly for longer commuting trips and less for shorter ones that comprise the majority of the

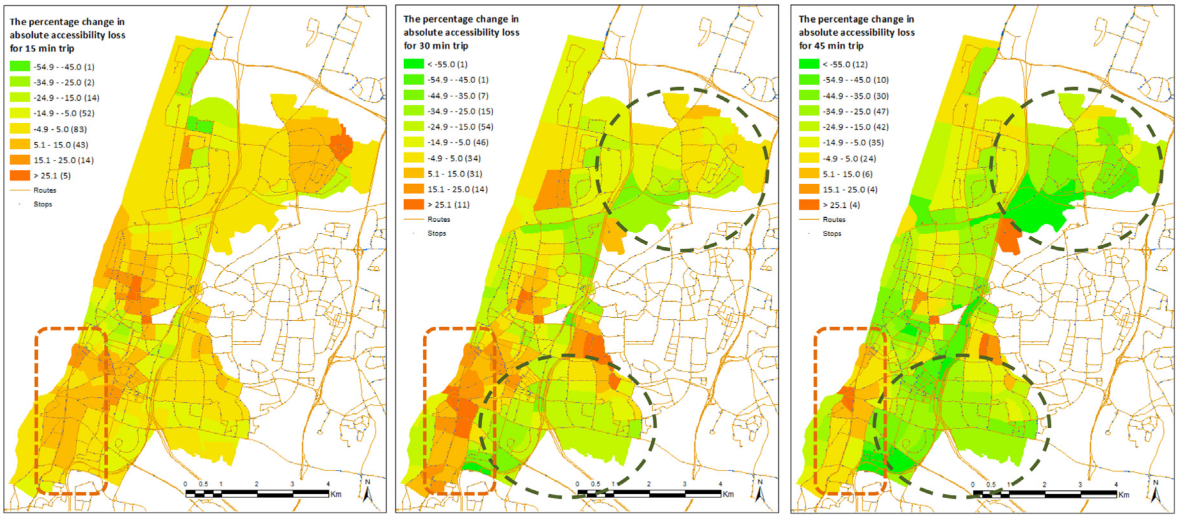

Fig. 4. The change of Absolute Accessibility Loss for commuting trips of 15′, 30′ and 45′ from all buildings in the city of Tel Aviv to all jobs in the Metropolitan Area in terms of access areas, aggregated by TAZ. The maps present the percentage change 100% * ($L_{i,O}(\tau)$, new – $L_{i,O}(\tau)$, old)/($L_{i,O}(\tau)$, old), related to the reforms to the transit network. Areas where the accessibility loss improved/declined are marked by circles/rectangles.

Table 3
Statistics of absolute accessibility loss L_O, in terms of access areas, with the old and new transit networks, averaged over the Tel Aviv TAZs.

Aggregate statistic	15′	30′	45′
Average accessibility loss before the reform*	23.3	32.0	29.8
Average accessibility loss after the reform*	23.4	29.5	23.0
Average accessibility loss change*	0.0013	−2.45	−6.80
STD of accessibility loss change*	3.89	8.46	10.27
Minimum accessibility loss change, by TAZ*	−24.6	−82.9	−88.7
Maximum accessibility loss change, by TAZ*	20.4	23.1	10.7
Fraction of the city area where the accessibility loss has improved	0.621	0.749	0.872
Fraction of the city population within the area of improved relative accessibility	0.541	0.687	0.901

* In millions of accessible worker-jobs.

Table 4
Statistics of normalized accessibility loss $N_{i,O}$ averaged over Tel Aviv TAZs, with the old and new transit networks.

Aggregate statistic	15 min	30 min	45 min
Average normalized accessibility loss before the reform	0.206	0.130	0.086
Average normalized accessibility loss after the reform	0.204	0.120	0.067
Average normalized accessibility loss change	−0.001	−0.011	−0.019
STD of normalized accessibility loss change	0.021	0.026	0.021
Minimum, over TAZ, of normalized accessibility loss change	−0.056	−0.165	−0.109
Maximum, over TAZ, of normalized accessibility loss change	0.065	0.066	0.075
Fraction of the city area where the normalized accessibility loss has improved	0.621	0.749	0.872
Fraction of the city population within the area of improved normalized accessibility loss	0.541	0.687	0.901

inner city travelers' trips.

The picture rising from Fig. 5 shows less pronounced changes brought about by the transit reform when seen through the normalized loss lens. Very few neighborhoods have an increase in the normalized loss. For the short commuting trips, the reform has a small albeit marginal decrease. For the longer trips the green hues dominate. However, some pockets where the loss has increased can be seen. These indicate places that the reform planners might well have overlooked. Moreover, some of these few neighborhoods also have a large increase in the absolute loss. This should have alerted the planners and regulators that services had been disrupted. These results demonstrate the importance of looking at both sets of the maps.

5. Discussion and conclusions

In this paper, we adopted a spatially-explicit method for calculating accessibility by different modes (car and transit) at a spatial resolution of individual buildings. This is very different from the common practice of transportation planners who start traffic

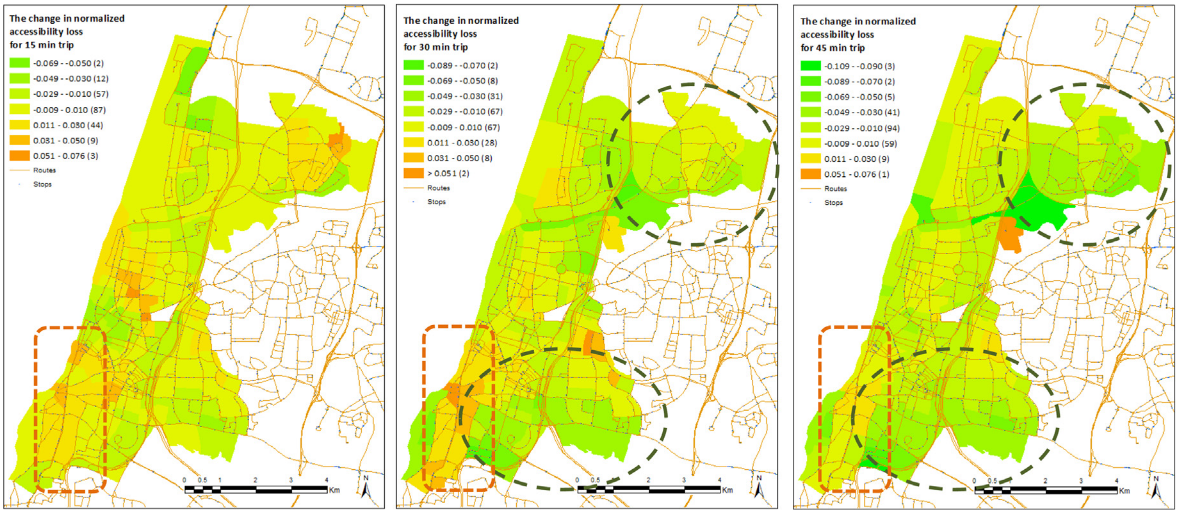

Fig. 5. The change in normalized accessibility loss in terms of access areas for commuting trips of 15′, 30′ and 45′ from all buildings in the City of Tel Aviv to all jobs in the Metropolitan Area at resolution of TAZ, calculated as $(N_{i,O}(\tau)$, new – $N_{i,O}(\tau)$, old)/($N_{i,O}(\tau)$, old). Areas where the accessibility improved/declined are marked by circles/rectangles.

analysis at the resolution of Transportation Analysis Zones (TAZ). This cumulative opportunities method takes account of potential accessibility (the number of activities reachable from a given building at a given time frame e.g. the number of jobs) to all relevant activities within a period of the day e.g. the peak hour. In particular, reflecting travelers' perception of the accessibility gaps between car and public transit we apply relative accessibility measures computed as the ratio between access or service areas of two competing modes.

We applied these high resolution computations to evaluate the equity impacts brought about by wide-scale changes in the transportation network. Apart for the well-known Gini index and Lorenz curve, we developed two new spatial indexes – the Absolute and Normalized Accessibility Loss for transit users. The *Absolute Loss* related to travel by transit instead of car allows comparison between the outcomes of a major transit change available to a few passengers and minor improvements that are available to many passengers. The Normalized Loss index is scalable and can compare between neighborhoods with different traveler population sizes and different mode shares. We consider that these two loss indices could well help planners and policy makers visualize the accessibility impacts of ex-ante plans or ex-post evaluation. Several researchers have recently commented on the dire need of transportation planners for clearer accessibility indicators (Boisjoly and El-Geneidy, 2017; Silva et al., 2017; Merlin et al., 2018; Deboosere et al., 2018).

In this respect, we investigate the changes in equity of accessibility to jobs (in terms of travelers' access area), during the morning peak hour, brought about by the recent bus reform in the Metropolitan area of Tel Aviv. We found that accessibility had indeed improved overall after the reform but mainly for longer commuting trips whereas for short ones the improvement was namely marginal. The equity improved for most but not for all neighborhoods. The main gainers were residents of two peripheral neighborhoods where pre-reform service levels were worse, while the losers were the residents of Jaffa (South-West of the city).

Future work can follow several directions: Service areas analysis will complement the access area view by showing how accessible are hospitals, universities, or transportation hubs like rail stations. In addition more time windows (evening peak and off peak), other mandatory and non-mandatory activities apart for work as well as extending the analysis to other modes such as bicycles and shared modes (car-sharing or ride-sharing) should be considered. This is particularly relevant from a vertical equity point-of-view considering social exclusion.

Second, if travel flows are known, we can estimate average travel times of the travelers starting at a certain origin or aiming towards a certain destination. The equity indices can be then straightforwardly modified to reflect travel times rather than activities (but beyond the scope of this paper).

Third, In addition to standard metropolitan transportation models, travelers' flows can be estimated in a much more spatially-explicit way using the data generated from transit smartcards or mobile phone calls (Trépanier et al., 2007; Calabrese et al., 2011; van Wee, 2016; García-Albertos et al., 2018). This type of data would fit quite well to the overall accessibility and the equity analysis framework we suggest. Moreover disaggregation allows migrating from traditional zone-based (4-step) transportation planning to full-blown activity-based generation models of travelers' expected activity-travel schedules (see reviews by Rasouli and Timmermans, 2014; Pinjari and Bhat, 2011; Dong et al., 2006). So far such activity-based generation models were estimated from survey data and aggregated to TAZ scale for running traffic and transit assignments. However, nowadays agent-based simulations such as MATSim (Horni et al., 2016; Rieser et al., 2007) can model daily multimodal traffic without applying for the TAZ tessellations. Instead they apply behavioral-based approach where each traveler-agent tries to find the best travel alternative by rerouting, switching departure times and modes or changing the destinations of some activities that allows maintaining a daily set of planned activities at the highest utility possible. High-resolution accessibility estimates and equity assessment can become standard extensions with such tools.

Fourth, PT vehicles always deviate from the planned timetables (as published on the GTFS) whereas the perception of passengers is based on real travelling and waiting times. To account for these deviations we can use data obtained from GPS transponders (Mondschein and Taylor, 2017; Cui and Levinson, 2018) that are now becoming publically available via real-time GTFS (Google, 2017). This would allow evaluating how large are perceived accessibility gaps that may be dictated by the largest and not average deviations of the actual schedule from the planned one given that recent studies have shown that subjective accessibility measures could be no less important than objective ones (Lättman et al., 2016).

Last, equity of accessibility should also become an integral part of the standard economic analysis for transportation infrastructure investments. In addition to the benefit-cost ratio, Gini, our absolute and normalized accessibility loss indices as well as other need-based indices can be used for equity analysis. These indicators are sensitive enough to enable multi-criteria evaluation (Feng and Zhang, 2012) for establishing a Pareto frontier connecting together efficiency, accessibility gain and their equity, thus allowing a balanced evaluation of projects' potential benefits to society and economy alike.

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