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Modeling relationships between the network distance and travel time dynamics for assessing equity of accessibility to urban parks

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ABSTRACT

Static models of accessibility are usually based on the fixed distance or Average Travel Time (*ATT*) models. Because of ignoring the traffic as a dynamic process affecting the accessibility through the change of Travel Time (*TT*), these models lead to unperceived temporal inequities. In contrast to the consideration of the temporal Variation of *TT* (*VTT*) in the previous studies, the variation of traffic-related *TT* and its relations with network distance has not been considered. In this study, relations between *VTT* and network distance to access urban parks in Tehran megacity has been modeled. Traffic maps at five times of day are used to produce *TT* maps of Traffic Analysis Zones (TAZs) to their 3-closest parks. Comparison of the Gini coefficients of accessibility show significant inequities of accessibility at different times of day. Relations between the distance, *ATT*, and TT_{max} are modeled by statistical analysis. Results show both *TT* and TT_{max} have significant positive relations with distance and traffic and reach their maximum at 6 p.m. Observation of significant relations between distance, *ATT*, TT_{max}, and *VTT* provides interesting knowledge for the conversion of temporal measures of equity (*TT*) to a physical measure of equity (distance). A simple application of these findings for effective management of the spatiotemporal inequities is the definition of critical distances from public services. As an example, to decrease the TT_{max} of TAZs to less than 12 min, their maximum distance to the closest parks should be less than 4 km. The developed approach can be adopted for the accessibility evaluation of the other public services, particularly the health and education centers.

1. Introduction

Sustainable urban development is one of the most significant objectives of urban planners and managers. The UK Government's definition of sustainable development relates to a better quality of life for individuals (Berke and Manta 1999; Choi and Ahn 2013). One of the key objectives of smart urbanism is to encourage spatial equity through equal access to affordable housing, economic activities, services, and facilities (El Din et al. 2013). So, accessibility is a key concept in assessing spatial equity in the distribution of services across the world (Van Wee 2016) and realizing sustainable urban development.

There are three principal components for measuring accessibility, including the destination of the travel, the origin of the travel, and the access cost from the origin to destination points (Bhat et al. 2002). Regardless of the fact that spatial accessibility is a dynamic concept in time, it has been often treated as a static concept in previous studies. In these studies, access costs to services are defined by a static Euclidean or network distances between a service recipient and a service provider. Although the physical distances between pairs of points remain constant, their access costs depend on travel time and traffic circumstances over different periods of time.

Considering time and space as the important parameters in the assessment of spatial equity of accessibility provides a four-dimensional space of analysis. Fixed and variable assumptions of location and time form a quadruple space of analysis as in Figure 1.

First-quarter is based on a fixed time and location, which is only valid for a single location at a given time. The second quarter assumes a single-time and uses variable locations for the assessment of equity as has been usually used in most of the previous studies. The third quarter is based on analysis of the accessibility while both dimensions of location and time are variable. This can be regarded as the most realistic space of analysis. Finally, the fourth quarter examines the accessibility of a single location during the time-varying conditions.

In reality, *TT* shows high variability because of the dynamics of traffic conditions in urban environments. Therefore, the problem of inequity caused by the temporal Variability of the *TTs* (*VTTs*) to public facilities is an important aspect that deserves special considerations. Particularly, an examination of relations between the spatial and temporal inequities can lead to more in-depth information about the inequities, effects of inequity on the quality of life of residents, and how they can be managed and controlled. Because of the higher risk of traffic at longer distances, spatial and temporal accessibilities are

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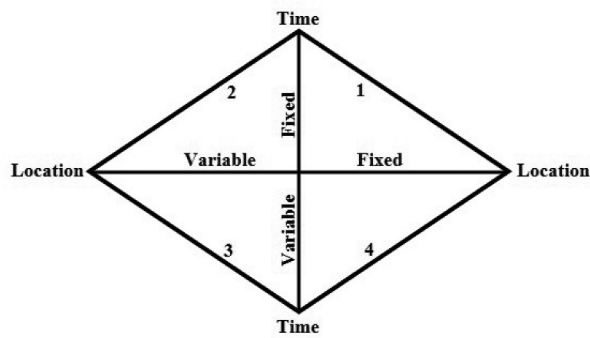
Figure 1. Four-dimensional space of analysis of the spatial equity of accessibility.

expected to show complex behaviors. This means residents located at higher distances from public services are exposed to higher *VTTs* in a given distance.

The problem of dynamic *TTs* has recently been addressed by some researchers. However, relations between distance and *TT* have not been considered and deserve careful considerations. Distance and time are the most frequently used parameters for measuring the equity of accessibility. Since distance is usually used as an access indicator in urban planning tasks, the development of models between *TT* and distance can provide valuable knowledge for the transformation of *TT* to distance, leading to a more precise definition of access time and the access distance standards in the planning process. Therefore, an important aim of this research is to model the relations between spatial and temporal access to urban parks, as an example of public services. The primary questions that are answered in this research are "How accessibility varies with time and how are spatial and temporal accessibilities related?" The Lorenz curve and the Gini coefficient are also used to determine how fair the accessibility is at different locations and times of the day.

The rest of the paper is organized as follows: Section 2 reviews previous literature on this topic; section 3 briefly introduces the methods of the study; section 4 introduces the study area and describes the modeling results of the relationships between the network distance and *TT* dynamics. Results of assessing the dynamics of spatial and temporal inequity of accessibility to urban parks and the application of the results for the management of the spatial and temporal inequity in the Tehran megacity as the case study area are also included in section 4. In Section 5 the conclusion of the research is put forward.

2. Literature review

A review of the previous works shows that the prime focus of many of the previous studies has been in the second quarter of the analysis space, and a few studies have addressed the third quarter as outlined in Figure 1. As an example, Mansour (2016) assessed the spatial pattern, distribution, and provision of public

health services using distances from demand points to providers extracted from the near analysis. In another study, Kompil et al. (2019) proposed a novel approach to map generic service accessibility in Europe. This approach was used to compare average distances to services and the number of residents who can walk or cycle to access the services in urban and rural areas. This study used the average distance at a fixed time to estimate and compare the accessibility of different regions and ignored the considerable differences between the travel distances and *TTs*. Similar ignorance can be found in some other studies (e.g. Lucy 1981; Talen 1997; Talen and Anselin 1998; Nichols 2001; Pasaogullari and Doratli 2004; Tsou, Hung, and Chang 2005; Omer 2006; Oh and Jeong 2007; Liao, Hsueh-Sheng, and Tsou 2009; Lotfi and Koohsari 2009; Zhang, Hua, and Holt 2011; Taleai, Sliuzas, and Flacke 2014; Ye and Xiang 2015; Dadashpoor and Rostami 2017; Kimpton 2017; Wu et al. 2017; Wen et al. 2018; Arranz-López, Soria-Lara, and Ángel 2019).

Some studies have considered *TT* instead of the travel distance for measuring spatial accessibility. For example, Fotini (2017) measured the individual accessibility to daily activities during a typical day, using an additional factor of activity space along with the places of activities, time, and temporal constraint. By considering different travel modes for quantifying accessibility as distances and *TTs*, Salonen (2014) analyzed the spatial patterns of realistic accessibilities to services. A similar study has been completed by Zhang et al. (2019) to assess the level of equity of access to community-based services. They assessed the accessibility of Chinese older adults by considering the frequency of using four travel modes of walking, cycling, bus-riding, and driving. In this study, the Average Nearest Neighbor (ANN) method was used to get the characteristic of the geographical distribution of community-based service centers. They finally proposed an alternative method to measure the accessibility of older adults by considering their travel behaviors. Tahmasbi et al. (2019) presented a multimodal accessibility-based equity assessment using the required *TT* for walking, using private cars or public transportation modes to access urban public facilities. In this study, the estimation of accessibility was based on the average values of *TTs* between the origins and destinations. Chang and Liao (2011) used the network and straight distances to show the role of mobility on the spatial equity of services and developed an integrated framework composed of two models of accessibility and mobility for measuring the spatial equity. Cheng et al. (2016) analyzed the spatial variation of medical centers and the accessibility to hospitals using *TTs*. Both the *TTs* of driving and using public transportation were computed and their mean values were used in the analysis. Lawal and Anyiam (2019) examined geographic access to Primary Health Care Facilities (PHCF) in Nigeria,

using the average *TT* from settlement areas to PHCFs. Results showed that more than 98% of the settlements have good access (less than 30 min), whereas, others are located in the poor (31–60 min) and very poor (over 60 min) access classes. Although the mentioned studies have used *TTs* instead of the travel distance and have enhanced the spatial equity measurement by considering different travel modes, the dynamic nature of *TTs* and the resulting impacts on the accessibility has not been well considered.

Some recent works have addressed the instant *TTs* and their dynamics for estimating Spatiotemporal accessibility and equity. As an example, Stępniak and Goliszek (2017) analyzed the spatial and temporal variation of accessibility to public transport in Szczecin (Poland). They analyzed the variation of *TTs* during a day using the averaged 15-min-long time periods. Results showed that some neighborhoods were affected by the high daily variation of accessibility and the low average accessibility values, which is called the "double-affected" issue. Hu et al. (2018) used a simulation model of traffic flow based on a macro-traffic simulation for estimation of *TTs* in various time periods during the day under free-flow and congested road conditions. The spatial accessibility of emergency medical services (EMS) in inner-city Shanghai was analyzed and classified into 5 different groups of accessibility (Q1-Q5), where Q5 represented the most deprived group in which the EMS cannot provide service in less than 8 min. Then, the accessibility of the area and number/percentage of the population in the Q5 were further analyzed during different times of the day. García-Albertos et al. (2019) used mobile phone records for constructing origin to destinations (OD) travel matrices to examine different scenarios for dynamic accessibility analysis. They examined four scenarios that included 1-the reference scenario based on the mean *TT* and destination attractiveness, 2 – the dynamic congestion scenario using the variable instant *TTs* and static destination attractiveness, 3- the dynamic attractiveness scenario based on the variable destination attractiveness and mean TT and finally 4- the dynamic accessibility scenario using the variable instant *TTs* and variable destination attractiveness. The analysis was conducted in three-time slots, including the morning peak, off-peak, and the evening peak. Results indicated that geo-located data can provide more accurate and realistic information than static or partially dynamic analyses. Zheng et al. (2019) considered the dynamic changes in transport costs to hospital services using public transit and self-driving modes of transportation. Instant *TTs* to access hospital services were considered at the peak and off-peak traffic hours of the day. Then, four baseline indicators including the minimum, maximum, average, and optimal weighted models of *TTs* were developed and analyzed to measure the accessibility of each residential area to hospitals. Supply and demand of the urban green spaces and their accessibility by elderlies in Salzburg (Austria) were studied by Artman et al. (2019). This study mainly focused on actual distances and barriers to reach and use green spaces by elderlies. Results of supply analysis showed the availability of green spaces in distances between 500 and 1000 m. But because of the existing barriers and difficulties of access for old-aged users, they prefer to use green spaces outside the service areas.

3. Methods

3.1. Accessibility measure

Gravity model as one of the most useful approaches for spatial equity measurement of accessibility is used in this study (Makri and Folkesson 1999). This model is based on the spatial interaction model and accessibility index measurement and considers both aspects of access costs and benefits, respectively expressed as the distance (or time) and attractiveness indices. The time-based accessibility index of this model can be expressed as:

$$\alpha_i^l(t) = \sum_{j=1}^{n} \left(w_j^l \times exp^{\left(-t_{ij}^l(t)\right)} \right) \quad (1)$$

where i and j are counters for recipients and services, respectively, $\alpha_i^l(t)$ is the index of accessibility of parcel i as a recipient to an urban service of type l at time t, n is the number of services of type l in the neighborhood of the parcel i, w_j^l is the attractiveness index of service j and $t_{ij}^l(t)$ is the *TT* from the recipient i to service j at time t.

The attractiveness index of service j depends on its capacity and quality and also the number of service users. Because of the lack of useful information about the capacity and quality of public service centers, particularly the parks, their size can be used as the representative of their capacity and quality. By assuming a negative linear relationship between the attractiveness index and the number of demanding users of a service center, attractiveness index of a service center can be modeled as a function of its size (area) and the demanding population who prefer to visit service j:

$$w_j^l = S_j^l / P_j^l \quad (2)$$

where

$$P_j^l = \sum_{i=1}^{I} Pop_i \quad (3)$$

in which S_j^l is the area of service j of type l, P_j^l is the total population who prefer to use service j and Pop_i is the population of TAZ $_i$ who visit service j.

3.2. Spatial and temporal accessibility relations

If the influences of other parameters such as accidents and car breaks-downs in urban areas are ignored, traffic plays the most important role in the definition of TT from a recipient such as i to service j. Therefore, TT is a dynamic parameter that varies at different times of a day due to different traffic conditions and speeds of movement. If the average speed of movement in different routes from origins to the closest service centers is represented by V_{avg}, then the average TT (ATT) from location i to j can be expressed as:

$$ATT_{ij} = V_{avg} \times d_{ij} \qquad (4)$$

where d_{ij} represents the distance from the location i to j. Instant TT (ITT) in a given time can be expressed as:

$$ITT_{ij} = ATT_{ij} + VTT_{ij} \qquad (5)$$

where VTT_{ij} represents the variability or errors of estimating ITT by ATT and can take positive or negative values. This means that ITT can be described by two components. One is the ATT, a systematic component which is the linear function of distance. Another one is the VTT which is a function of both distance and traffic and varies with time and traffic conditions. $ITTs$ of different routes can be estimated using the real-time traffic maps, data of traffic sensor networks, and other related available information from the internet networks. By assuming ATT as the linear function of distance, this parameter can be estimated by collecting representative samples of daily traffic conditions and fitting a linear model between the distance of all the origins from their destination service centers and $ITTs$ of different sample traffic conditions.

$$ATT_{ij} = f_1(d_{ij}), or ATT_{ij} = a \times d_{ij} + b \qquad (6)$$

By calculation of the difference between the ITT and ATT, VTT for each route, distance and time can be estimated from:

$$VTT_{ij} = ITT_{ij} - ATT_{ij} \qquad (7)$$

Because of the spatial autocorrelation effects, closer areas are expected to be more similar than the farther places. So, it is expected that diversity of traffic, car speed, and route conditions increase with the distance, resulting in an increasing trend of VTT with the distance. Then VTT for each distance and time can be estimated by modeling the relations between the distance and VTT.

$$VTT = f_2(d) \qquad (8)$$

and ITT can be represented as a function of distance:

$$ITT = f_1(d) + f_2(d) \qquad (9)$$

Different statistical properties of TT and VTT such as the maximum, minimum, and average values for different time periods can be estimated and used in the assessment of access equity in different distances and times. As an example, maximum values of TT (TT_{max}) in a given time period is an important criterion which is usually intended to be minimized or preferred to be less than a certain threshold in equity assessment and planning. This parameter for each distance can be estimated from:

$$TT_{max} = ATT + VTT_{max} = f(d) \qquad (10)$$

So, modeling of ITT and TT_{max} as a function of distance, as in equations 9 and 10, can lead to the transformation of time to distance and effective management of both the spatial and temporal inequities.

3.3. Access equity assessment

Measuring the accessibility only makes a visual index over the specified spatial units, and it does not show the equity of distribution of services (Guzman, Oviedo, and Rivera 2017; Lucas, van Wee, and Maat 2016; Neutens et al. 2010; Van Wee and Geurs (2011)). Among the existing indices, the Lorenz curve, and the Gini coefficient as the scale-independent indicators have gained a broad application (Xu et al. 2018).

In this study, the Gini coefficient is applied to measure the level of the inequity of the accessibility at different times of the working day. The difference between the Gini coefficients got at different times of the day can show the effects of urban traffic on the equality of access to services during the day. The Gini coefficient is equal to the ratio of the area of the gap between the Lorenz curve and the 45-degree line of complete equality over the total area under the line of complete equality (Shirmohammadli, Louen, and Dirk 2016) (Equation 11).

$$GC = 1 - \sum_i (Y_{i+1} + Y_i)(X_{i+1} - X_i) \qquad (11)$$

where GC is the Gini coefficient value, Y_i is the cumulative proportion of the accessibility and X_i is the cumulative proportion of the population in the study area (Tahmasbi et al. 2019; Brown 1994; Welch and Mishra 2013). In this paper, the accessibility index is measured for each TAZ and the total population of each TAZ is considered as X_i in the Gini coefficient equation. GC value equal to zero and one respectively indicates perfect equality and perfect inequality in accessibility among TAZs.

4. Practical experiments and results

4.1. Case study area

The case study area is the Tehran megacity, the capital of Iran. Tehran is divided into 22 metropolitan regions. Each region is divided into several districts, and, finally, each district includes several local neighborhoods. In

the latest official national census in 2016, Tehran had a population of 8,737,510 extended in about 640 square kilometers. The city is divided into 560 TAZs which are treated as the service demanders in this study (Figure 2).

4.2. Distribution and supply of green spaces

Green spaces in the study area show uneven patterns of distribution. Correlation analysis of population and park area density in TAZs shows inverse relations between these two; with low population density TAZs having higher park area densities, especially in the western parts of the city (Figure 3). This may be because of the larger size and number of available bare lands and open spaces in the western parts of Tehran (regions 21 and 22). Also, the construction of Lunar Cities around the city for the accommodation of the overflow population of Tehran has led to higher park densities in these regions. This has resulted in a higher number of extensive parks in fewer populated areas, while most of the small parks are located in densely populated areas (Figure 3).

Distribution of the number of parks as the supply source in different distances from the TAZs as the demanders is highlighted in Figure 4. As seen, about 50% (59 parks from the total of 114), are located in distances less than 1,000 m from the TAZs, and the most parks (about 85% of parks, 97 from 114) can be reached in less than 3,000 meters distance from the TAZs. The number of existing parks shows sharp increases from 500 to 2500 m. After this, an increase in the distance leads to a minor increase in the number of parks from 97 to 114. Only 33 parks that are about 29% of the existing parks are in distances closer than 500 m. On the other hand, as highlighted in Figure 3, inverse relations between the park and population density lead to the intensive occupation, and therefore, lower attractiveness of parks in populated areas. So, the situation of accessibility and attractiveness from the supply side, particularly for children and elderly people, is well below the acceptable levels, and accessibility by driving a car is the usual practice.

4.3. Travel distance and TT estimation

Measuring access to services has two principal elements: the service provider and the service receiver. In this paper, Tehran traffic analysis zones and the
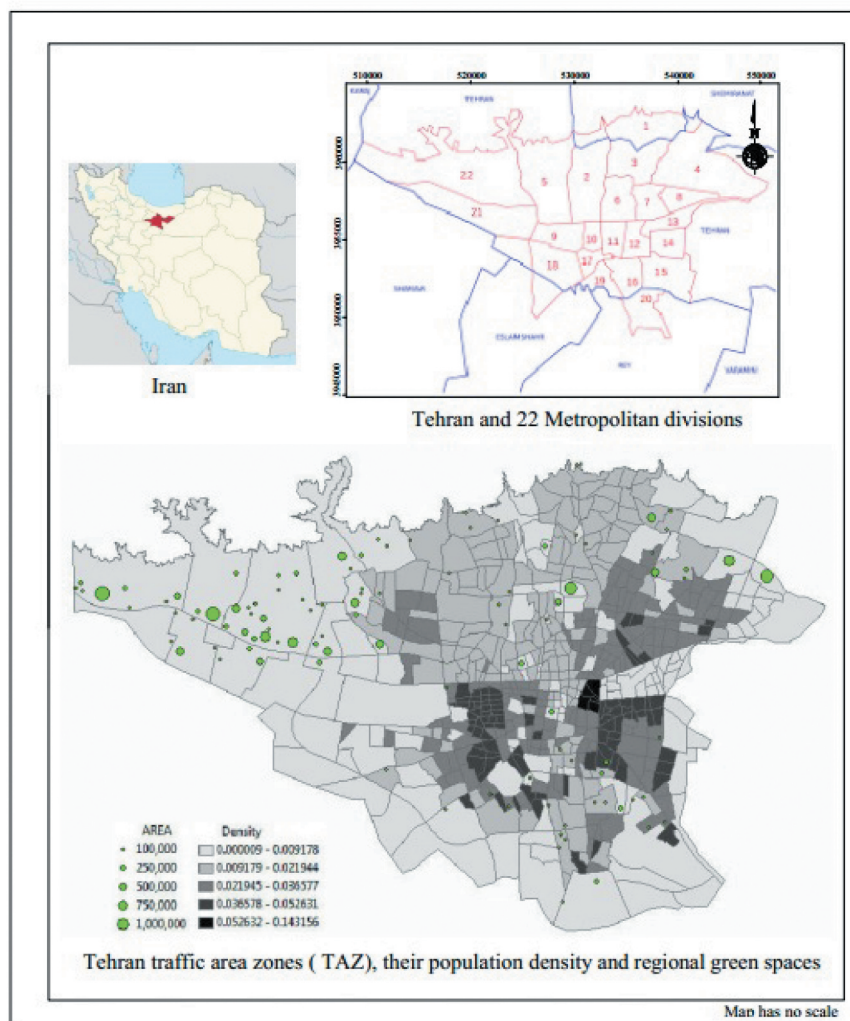

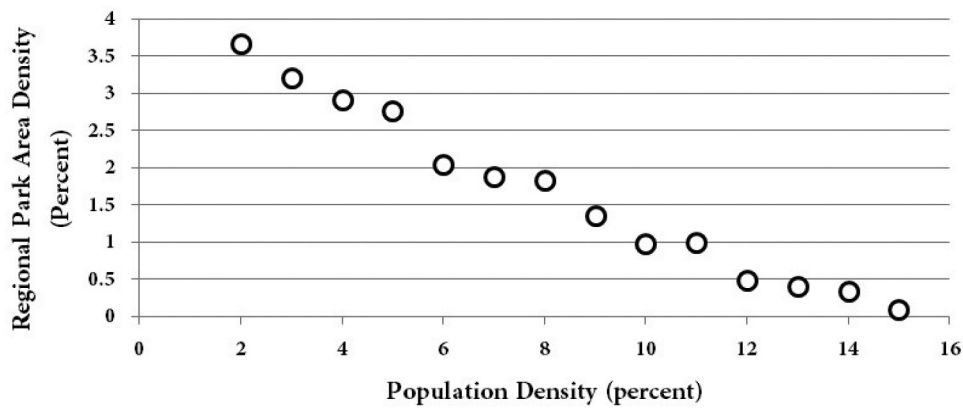**Figure 2.** Green space distribution and geographic location of the Tehran megacity as the case study area.

Figure 3. Relations between population density (horizontal axis) and park area density (vertical axis) in the study area.
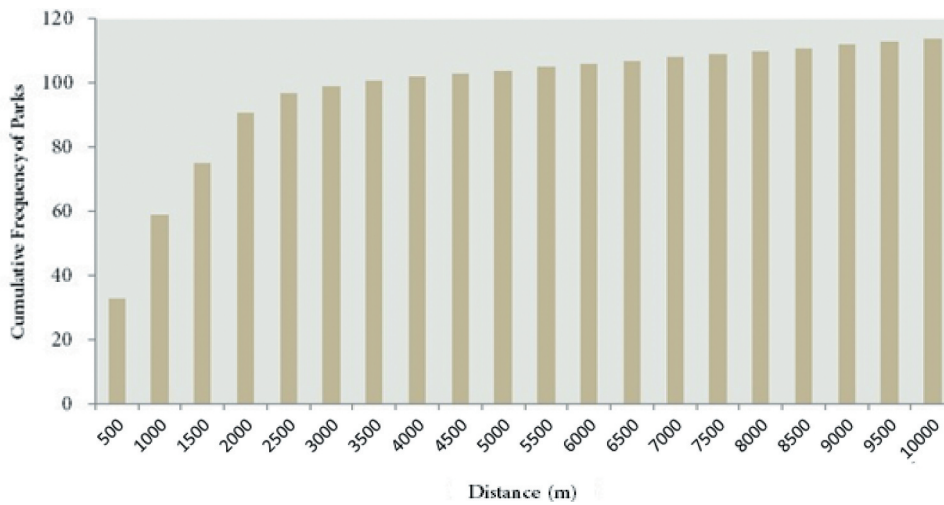

Figure 4. Cumulative frequency of parks located in different distances from TAZs in the study area.

urban parks have been considered as the service receivers and providers, respectively. The Network Analyst, OD (origin-destination) Cost Matrix tool of ArcGIS has been used to measure network travel distances between TAZs and urban parks with considering length as the impedance function. Due to the lack of reliable data on the exact location of city park entrances, centroids of TAZs and urban parks have been used as the origins and destinations, respectively.

To avoid limitations caused by assuming each service user to choose only one service, in this study, the spatial accessibility of TAZs to their three nearest parks has been analyzed. Considering several adjacent services instead of the nearest one can be of particular interest in the assessment of the access equity to the alternative parks in a larger context. As an example, two residents may have equal distances from their first closest parks, whereas they may have different access to the alternative parks because of the differences in their distances from the second and third closest parks.

One of the important objectives of this study has been to estimate, and map *TTs* of all TAZs to the three closest parks at five different times of the

working day. So, because of the need for spatial data of traffic conditions, numerous TAZs and OD points, and also spatially continuous and real-time data of traffic conditions provided by the Google Maps, these maps have been used as the source of traffic data. Traffic maps provide detailed spatial and temporal information on traffic conditions, which can be useful for mapping and understanding the spatial patterns of traffic conditions and their effects on distance-time relationships.

Real-time traffic conditions of the study area were monitored and gained for five samples of varying traffic conditions during the working day times at 7 a.m., 9 a.m., 12 p.m., 3 p.m., and 6 p.m., using the Google Maps. Different traffic patterns and representativeness of these times were the main reason for their selection. In Google traffic maps, street segments are constantly labeled with three traffic classes named "Light", "Moderate" and "Heavy" which are respectively equivalent to maximum speeds of 80, 50 and 30 km/h according to the local traffic control agencies. For the computation of travel time in different ODs, the existing web-based local route planning tools based on the Google Maps were used to calculate the average speeds in each of the three traffic classes.

These respectively resulted in average speeds of 10, 24, and 58 km/h for the heavy, medium, and light traffic classes. Then the calculated average speeds and traffic maps of five different times were used to compute the total *TT*s for ODs by measuring and summation of the *TT*s of different segments of the networks connecting each TAZ to the three closest parks.

4.4. Relationships between distance, TT and VTT

Evaluation of relations between distance and *TT* are mainly based on the use of public or private cars. The principal reason for this choice is the scattered patterns of park distribution, acute sensitivity of this transportation mode to traffic conditions, and its frequent use to access parks in the study area.

Results of examining relations between the network distance and *TT* at five sample times of a day are presented in Figure 5. Traffic maps show that the heaviest traffic occurs at 6 p.m., while the lightest traffic is observed at 12 p.m. As expected, scatter plots show that complicated relationships composed of linear functions with varying slopes exist between travel distance and *TT*. This shows that *TT* inidicates considerable variability for a distance which increases with distance.

For examination of the relations between *TT* and distance, five sample times of *TT* were used to produce daily data of *TT*. Then, distance values from the three closest parks were classified in nine classes with equal widths of 2 km. By calculation of daily average and hourly standard deviation of *TT*s within each distance class, data of *ATT* and hourly *VTT* were produced. This data was then used for evaluating the relations of hourly *VTT* and daily *ATT* with the distance. Figures 6 and 7 highlight the results of these analyses.

Observation of the change of *VTT* as a function of distance in five unique traffic conditions in Figure 7 shows interesting patterns. In light traffic conditions at 12 p.m., *VTT* shows a slight increase with an increase in the distance and then no change or even some slight decrease in longer distances of over 12 km. But the increase of the traffic density results in a sharper increase of *VTT* at longer distances leading to nonlinear increases with the distance (Figure 7). As shown in the Figures 6 and 7, both the *TT* and *VTT* show increasing trends with the increase of the distance, where, in contrast to *TT* which linearly increases with distance (Figure 6), *VTT* shows an exponential increase with the distance (Figure 7). These observations show the fact that longer distances are exposed to higher *VTT*s caused by traffic congestion, resulting in severe inequities in longer distances. Severe increase of *VTT* in longer distances, particularly during peak traffic hours, can be attributed to the increase of the diversity of access roads and traffic conditions at these distances.

The magnitude of *VTT* in a distance in Figure 7 is an example of traffic-related and dynamic inequity of access to urban services. Because of the increase of the traffic effects on longer traveling distances inside the urban areas, the inequity of *TT*s shows increasing trends in longer distances from the service centers. Therefore, considerable inequities that increase with the distance and density of traffic exist between residents with equal distances from the service centers. In contrast to the inequity of distance and *ATT* between residents, that are well understood and explained in previous studies, temporal dynamics of the inequity of *TT* and their increase with the spatial distance can be regarded as an example of the unperceived inequity. These results confirm the fact that using static indices such as the travel distance or *ATT* for measurement of inequity can lead to ignorance of considerable inequities.
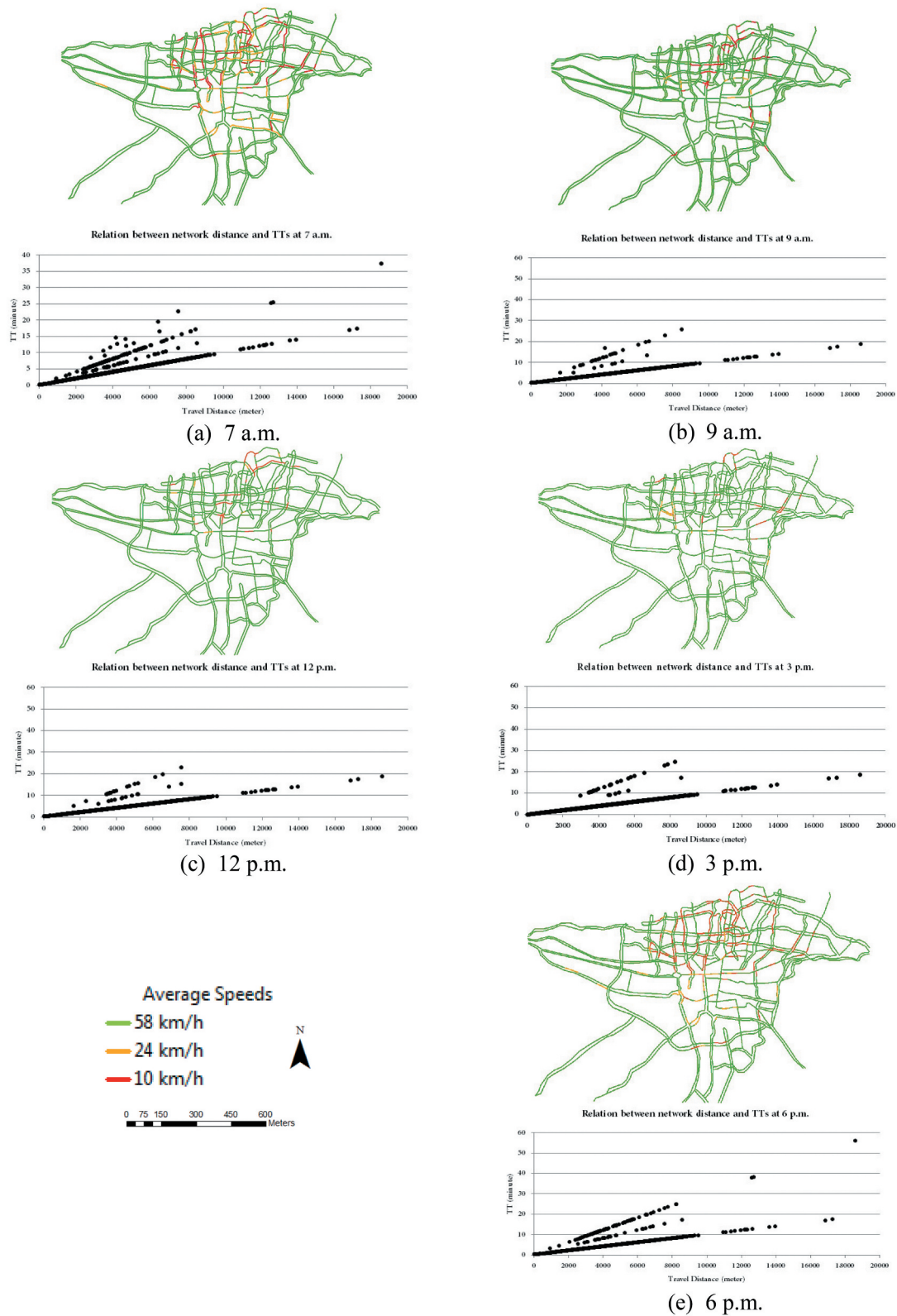
4.5. Comparison of accessibility maps based on ATT and ITT

As shown in Figure 6, the distance and *ATT* during the day are linearly related. Therefore, classified maps of travel distances and *ATT* to parks are expected to show similar results. For a better understanding of the geographic context of the study area, the distances of each TAZ to its top-1, top-2, and top-3 closest parks are separately mapped and shown in Figure 8.

It can be seen that TAZs located in the eastern and southwestern parts of the study area is over 5 km away from their first nearest parks (Figure 8(a)) and their accessibility status is even getting worse in the second and third nearest parks (Figure 8(b-c)). Figure 8(d-f) show the results of using two numbers of the closest parks. The result of using the three closest parks is shown in Figure 8(g). It is interesting to see how the order of selected closest parks (first, second, or third) heavily affects the accessibility of the residents (Figures 8 and 9). Distribution of parks in different distances shows normal patterns and the maximum number of the first, second, and third closest parks are respectively located in 3, 4 and 5 km from the TAZs (Figure 9). Access to two and three numbers of the closest parks requires much higher travel distances and TTs. As an example, to visit two of the three closest parks, most residents have to travel about 10 km (Figure 9). Therefore, consideration of accessibility to over one nearby park provides more useful accessibility information, not provided by considering only the one closest park.

For visualization of the spatial effects of temporal dynamics of inequity, the gravity model as expressed in equation 1 was used to produce and compare two types of accessibility maps. One is the *ATT*-based

Relation between network distance and TTs at 7 a.m.

(a) 7 a.m.

Relation between network distance and TTs at 9 a.m.

(b) 9 a.m.

Relation between network distance and TTs at 12 p.m.

(c) 12 p.m.

Relation between network distance and TTs at 3 p.m.

(d) 3 p.m.

Average Speeds
— 58 km/h
— 24 km/h
— 10 km/h

Relation between network distance and TTs at 6 p.m.

(e) 6 p.m.

Figure 5. Traffic maps showing average speeds and dynamics of three traffic classes and relations between the network distance (meters in the horizontal axis) and *TTs* (minutes in the vertical axis) at five sample times.

accessibility index using *ATTs* instead of the dynamic *TTs* in equation 1. This leads to the production of only one accessibility map. Another is the *ITT*-based accessibility maps of TAZs which use instant *TTs* instead of the *ATT* and results in the production of five temporal accessibility maps, one for each of the sample times.

All the six resulting accessibility maps were classified into three classes of accessibility. These include "favorable" (*TT* of fewer than 8 min), "moderate" (*TT* of 8–20 min) and, "unfavorable" (*TT* of more than 20 min), respectively showing high, medium, and low accessibilities. So, the last class highlighted the
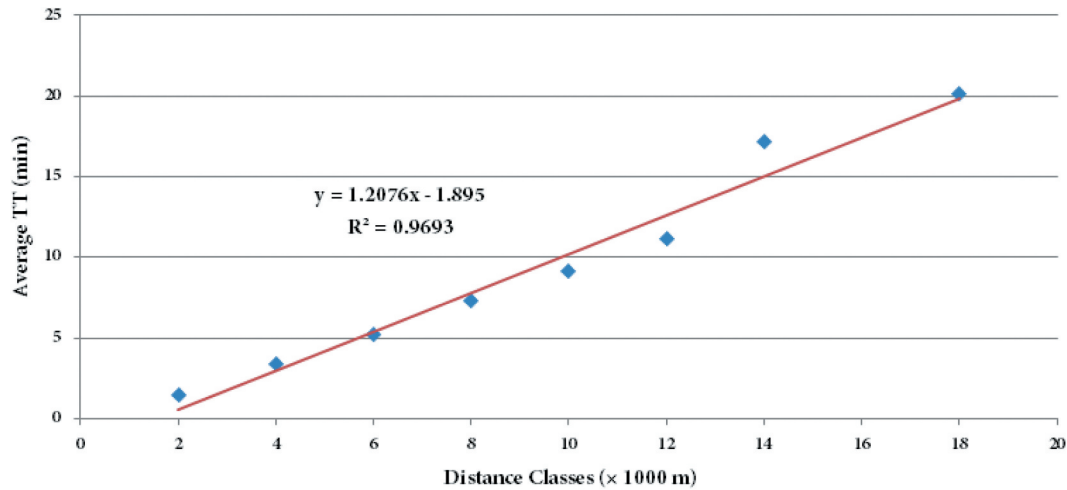
Figure 6. Linear relations between the distance to the 3 nearest parks of residents and average daily TT of distance classes.
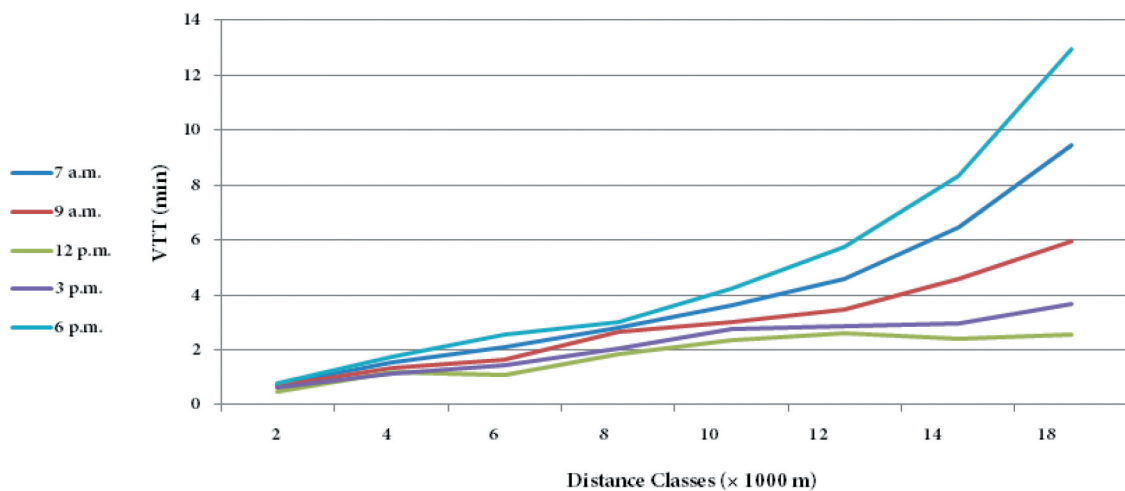
Figure 7. Nonlinear relations between the distance to the 3 nearest parks and *VTTs* of distance classes in five sample times (7 a.m., 9 a.m., 12 p.m., 3 p.m. and 6 p.m.) and a sharper increase of *VTT* in longer distances during the two peak traffic hours of 7 a.m. and 6 p.m.

deprived areas. Figures 10 and 11 highlights the distributions of the areas of unfavorable TAZs at five sample times of a working day.

Significant impacts of traffic are evident in the variability of total areas of TAZs with unfavorable accessibilities. Such that the total areas of the unfavorable class reach their maximum of more than 10,000 ha at 6 p.m., the most traffic-congested time. This area is, considerably higher than those of the areas of unfavorable classes, 7600 ha at 7 a.m., 4607 ha at 9 a.m., 3234 ha at 12 p.m. and 4244 ha at 3 p.m.

Examination of the extracted unfavorable areas shows that "time" and "traffic" play important roles in the inequity status of accessibility of TAZs (Figure 11). An interesting result of this examination is the dynamic nature of inequity. As an example, a region may be favorable at 12 p.m. and unfavorable at 6 p.m., which is in contrast with the static accessibility approaches. This inequity can be more obvious in access to some critical service centers such as health centers or hospitals, where there is no choice of time and one has to use

the service at any unexpected time. As an example, two residents may have equal fixed (time or distance) accessibilities, but they may face very unequal conditions and the chance of access in an urgent case of need for health care and hospital services. The inequity of this type can be managed by the estimation and control of the TT_{max} as outlined in equation 10.

4.6. Assessment of access equity of TAZs

In order to assess the equity of accessibility of TAZs to their three closest regional parks at five times a day, the Lorenz curve was plotted for each time. Figure 12 shows the Lorenz curve where accessibility levels are compared to the residential population in each TAZ. These curves show that the lowest and highest accessibility, respectively, belong to 6 p.m. and 12 p.m., with Gini coefficients of 0.26 and 0.53 respectively. This means that if accessibility is interpreted as the number of opportunities, at peak traffic hour (at 6 p.m.), 80% of the population share only 33% of the regional park opportunities and, conversely,
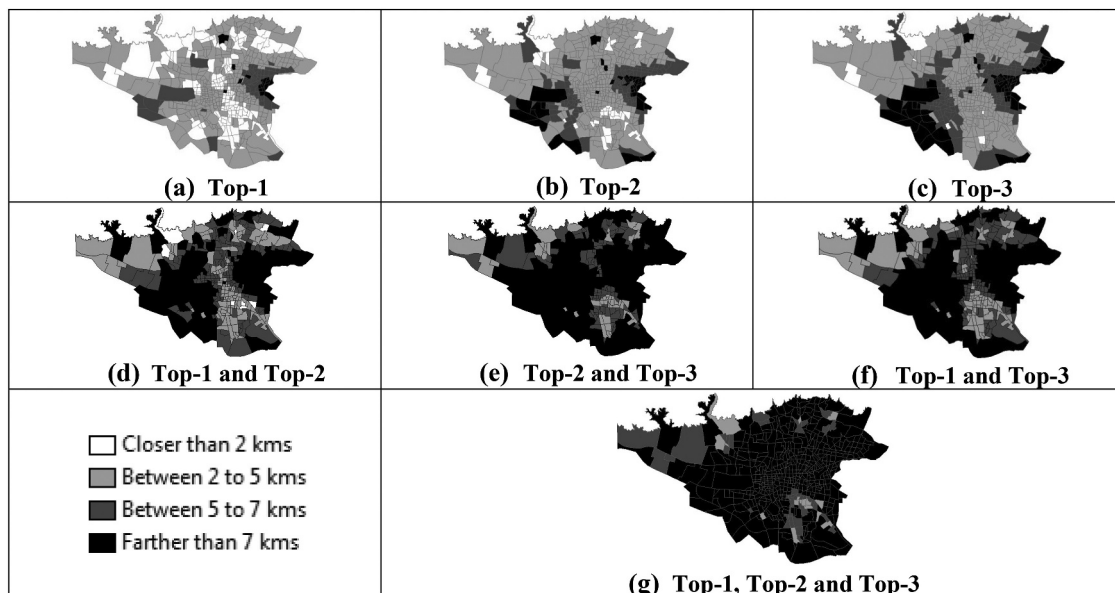
Figure 8. Distance of TAZs to their (a) top-1, (b) top-2, (c) top-3, (d) top-1 and top-2, (e) top-2 and top-3, (f) top-1 and top-3 and (g) top-1, top-2 and top-3 closest parks.
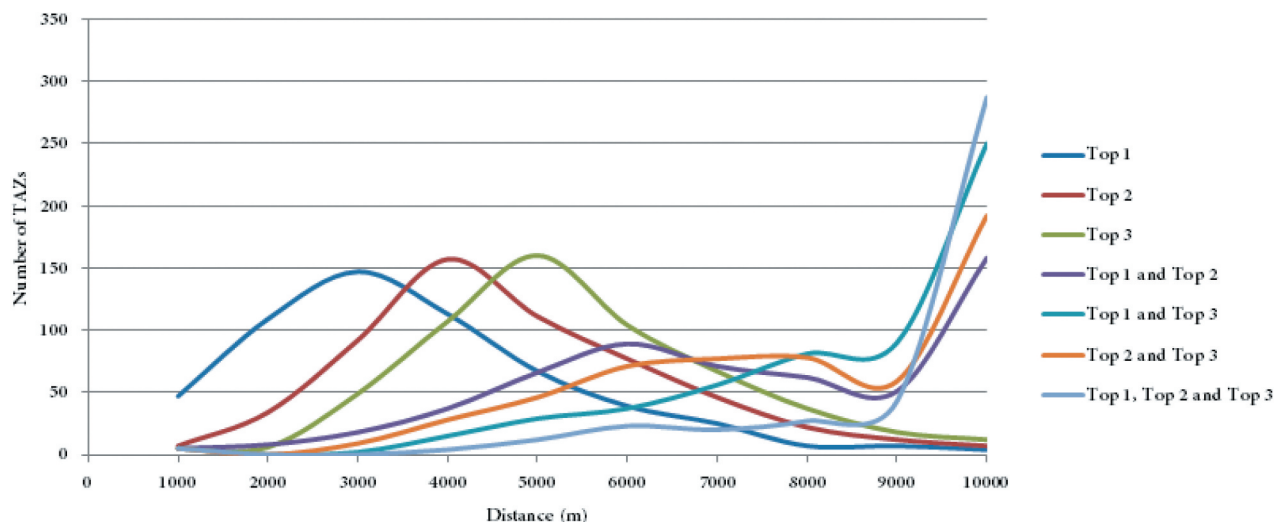

Figure 9. Number of TAZs in different distances from their top-1, top-2, top-3, top-1 and top-2, top-1 and top-3, top-2 and top-3, top-1 and top-2 and top-3 closest parks.
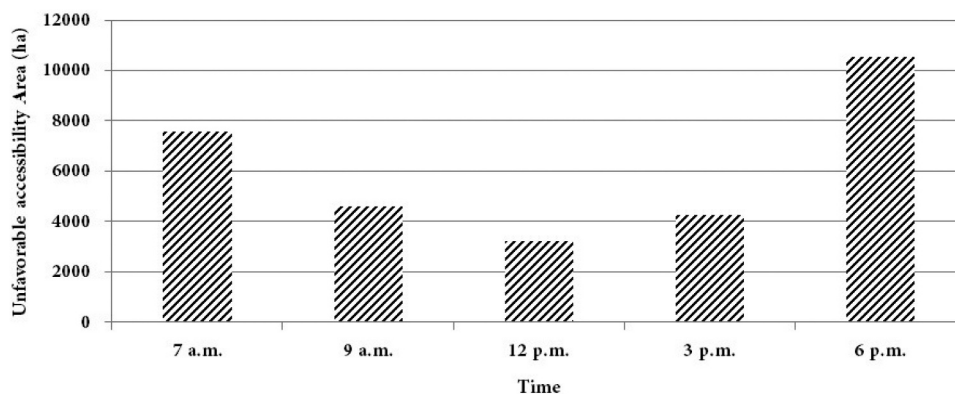

Figure 10. Total area (ha) of TAZs with unfavorable accessibility (more than 20 min) to the 3-closest parks.

20% of the remaining population share 77% of the opportunities. While at off-peak traffic hours (at 12 p.m.), 80% of the population share about 70% of the regional park opportunities, and conversely, 20% of the remaining population share 30% of the opportunities. In the same way, at other times (at 7 a.m., 9 a.m., and 3 p.m.), 70% of

(a) 7 a.m.   (b) 9 a.m.   (c) 12 p.m.

TAZs with unfavorable accessibility

(d) 3 p.m.   (e) 6 p.m.
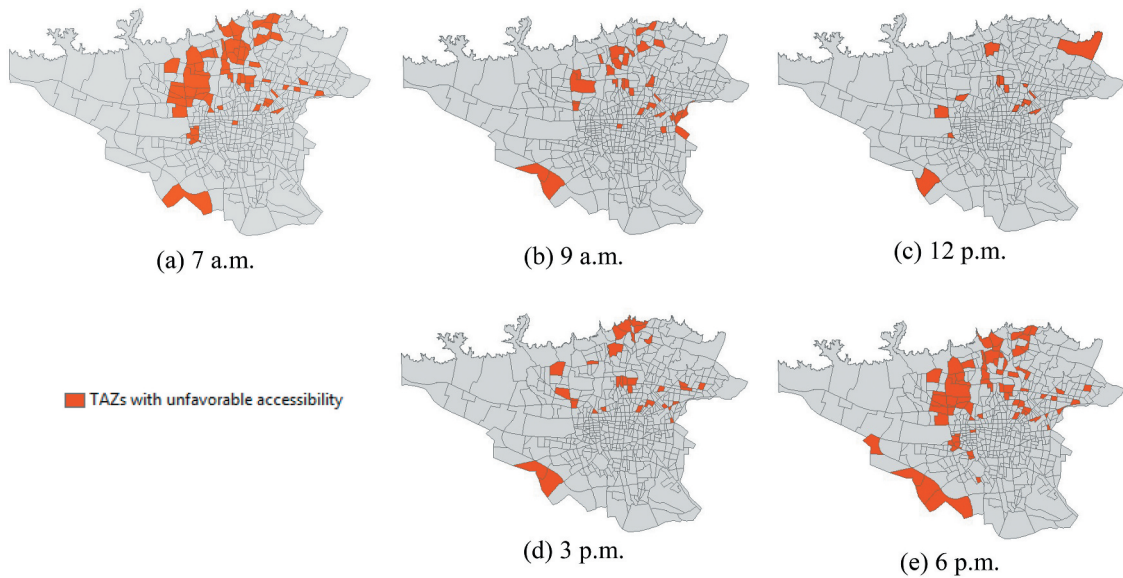
Figure 11. Maps showing the spatial distribution of unfavorable areas (with travel times of more than 20 min) at 5 times (7 a.m., 9 a.m., 12 p.m., 3 p.m. and 6 p.m.) of a working day and a significant increase of these areas at 7 a.m. and 6 p.m., the most traffic-congested times.
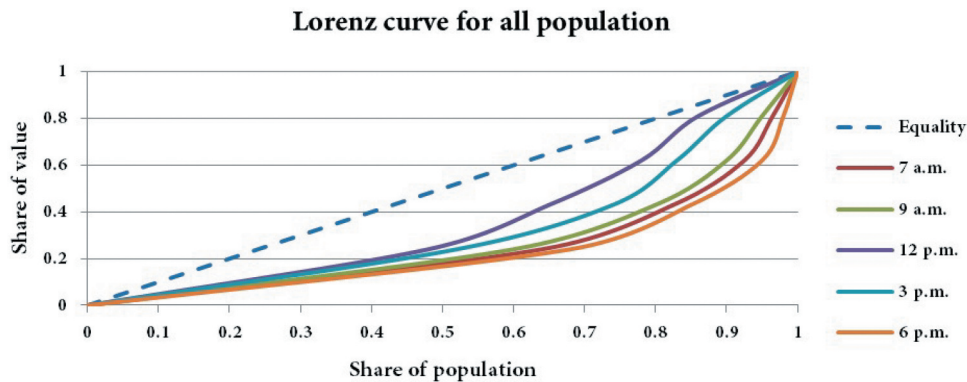
Figure 12. Lorenz curve of all population of the study area, for sample times of 7 a.m., 9 a.m., 12 p.m., 3 p.m., and 6 p.m. during a working day.

the population respectively share 27%, 30%, and 38% of the opportunities.

Differences in the Lorenz curves at different times of day highlight the temporal inequity of accessibility in the study area, which results from varying traffic conditions during the day. The practical effects of these inequities would depend on the demand and service type. As an example, temporal inequities and a sharp increase of VTT with distance and heavy traffic conditions would be more significant in accessing urgent demands for emergency services, hospitals, and clinics. In contrast, in the case of accessing time-limited services such as offices and schools, accessibility during the working hours can be critical.

4.7. Practical application in inequity management

For a demonstration of the usefulness of the proposed approach for spatiotemporal inequity management, daily ATT and TT_{max} of each TAZ to the three closest

parks were calculated, using five samples of daily TT. Investigation of the relations between the daily ATT and TT_{max} showed two interesting patterns (Figure 13). One pattern which is dominant and highlighted with the fitted line in Figure 13, is where ATT and TT_{max} show a strong linear relationship, and according to equation 10, $VTT = 0$, and $ATT = TT_{max}$. This represents TAZs with minimum sensitivity to traffic conditions, which are mostly concentrated in low values of $ATTs$ (less than 7–8 min) and negligible VTT during the working day.

Another pattern belongs to TAZs with TT_{max} greater than ATT ($VTT > 0$), which are highly exposed to traffic conditions (Figure 13). This pattern shows high variability of TT in relation to the fitted line to the first pattern which increases with the increase of ATT and TT_{max}.

Due to major differences of these two patterns, high temporal variability of TT in pattern 2, TAZs of this pattern are more important for spatial equity management. Because of this, two patterns have been discriminated against and separately considered. Separation of these two patterns is
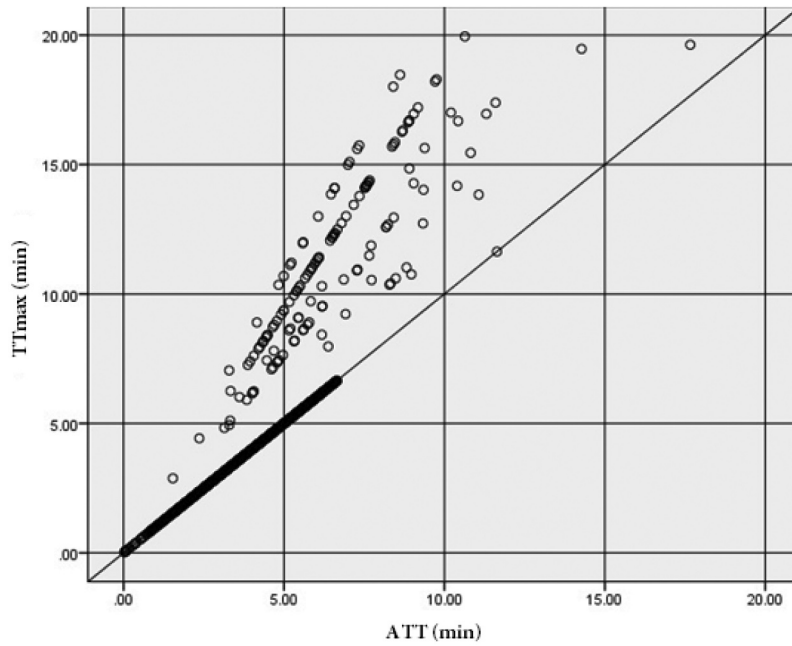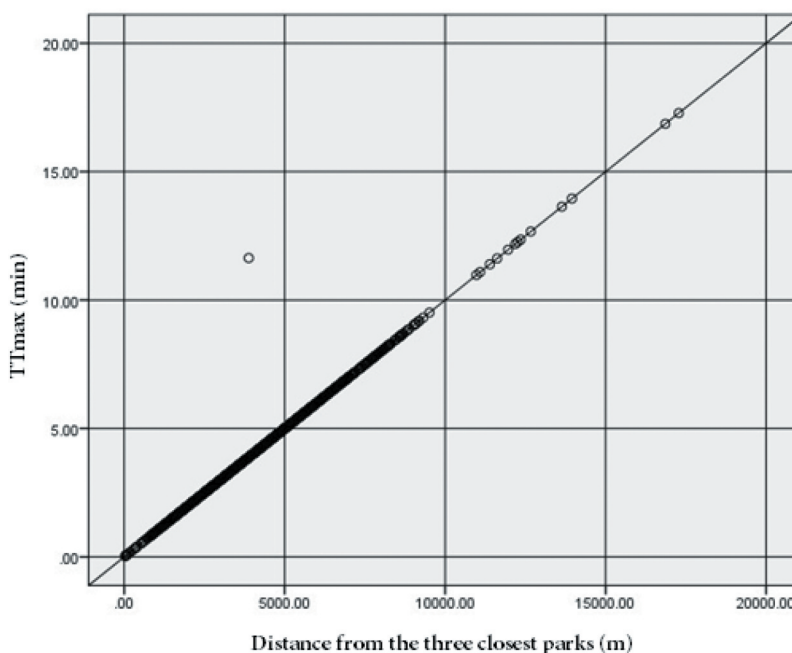
Figure 13. Relations between the daily TT_{max} (vertical axis) and ATT (horizontal axis) for the three closest parks in the study area.

helpful as they display uncommon TT behaviors. These patterns are respectively, referred to as pattern 1 and pattern 2. Consideration of the relations between the TT_{max} (or ATT) and the distance of pattern 1 from the three closest parks shows strong linear relationships, showing the one-to-one relationships between the TT_{max} and distance (Figure 14). Equation of the fitted line between the TT_{max} (in min) and the distance, represented as d (in meters) is expressed as $TT_{max} = ATT = 0.001d$.

Therefore, as an example of applying this equation, the required travel distance for TAZs of pattern 1, to access at least one of the three closest parks in less than 5 min, is less than 5 km. By applying this distance threshold for data of pattern 1, TAZs of pattern 1 are divided into two accepted and rejected classes, respectively for having less (or equal) and more than the TT_{max} of 5 min. Frequency of TT_{max} of these two classes as presented in Figures 15 and 16, which demonstrates the validity of this discrimination. As seen, maximum and minimum values of TT_{max} respectively in the accepted and rejected classes are equal (5 min) which is in agreement with the objectives for distance-time based discrimination of TAZs for inequity management.

As control of the TT_{max} to lower than the desired value is the main objective in equity management

Figure 14. Strong linear relationship between the TT_{max} (vertical axis) and the distance from the three closest parks (horizontal axis) for TAZs of pattern 1 in the study area.
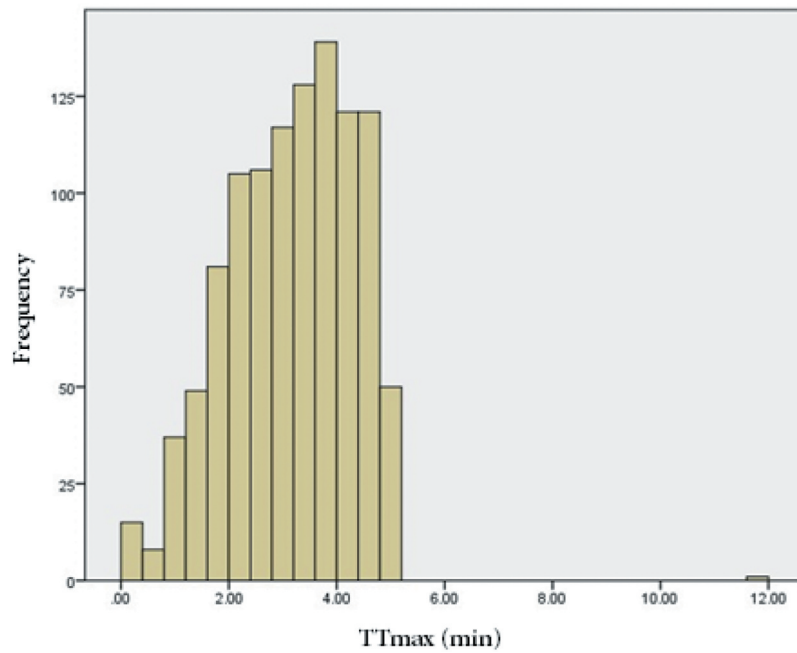
Figure 15. Frequency of $TT_{\max}$ distribution (with maximum $TT_{\max}$ of 5 min) in TAZs of pattern 1, selected for having distances of less than 5 km from at least one of the three closest parks.
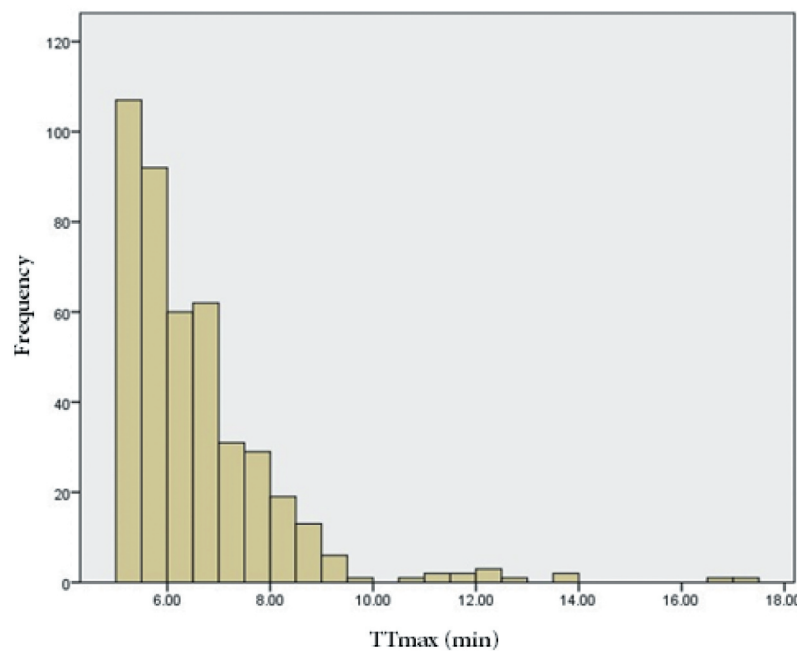
Figure 16. Frequency of $TT_{\max}$ distribution (with minimum $TT_{\max}$ of 5 min) in TAZs of pattern 1 selected for having distances of more than 5 km from the three closest parks.

projects, so TAZs of pattern 2 with an acute sensitivity to traffic conditions provide important challenges for TT equity management. Figure 17 highlights the relations between the $TT_{\max}$ and distance from the three closest parks for data of pattern 2. As shown, there are two minor patterns with linear relations with distance but with different slopes. However, due to the importance of controlling the maximum values of TT, the pattern with the lower slope is neglected, and the dominant pattern with higher values of $TT_{\max}$, sharper

slope, and stronger linear relations with the distance is selected for the line fit (Figure 17).

Equation of the fitted line for data of pattern 2 is $TT_{\max} = 0.003d$, where the increase of the $TT_{\max}$ as a function of d is three times more than that of the pattern 1.

For a practical test of the validity of this equation, as an example, the required travel distances to access at least one of the three closest parks in less than 12 min are less than 4 km. By applying this distance threshold
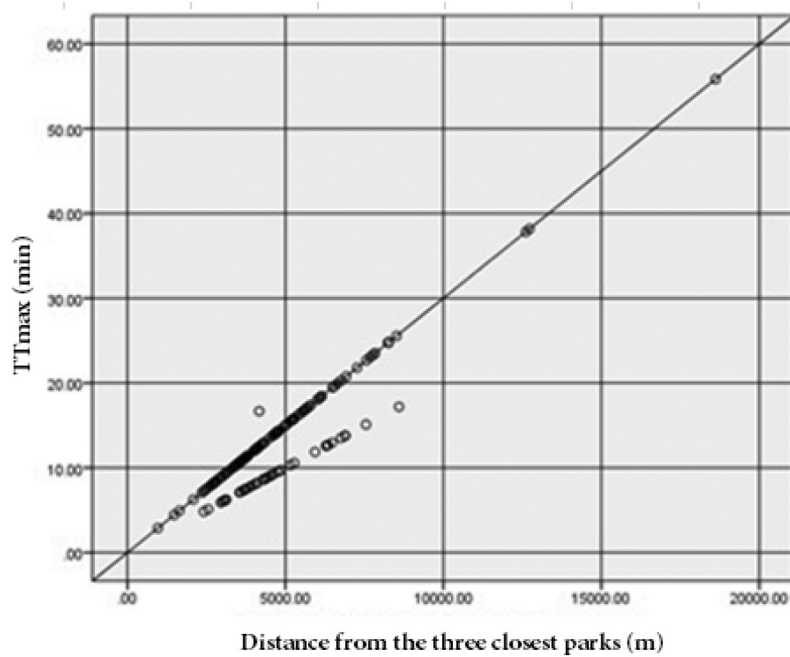
Figure 17. Relations between the TT_{max} (vertical axis) and the distance from the three closest parks (horizontal axis) for TAZs of pattern 2 in the study area.
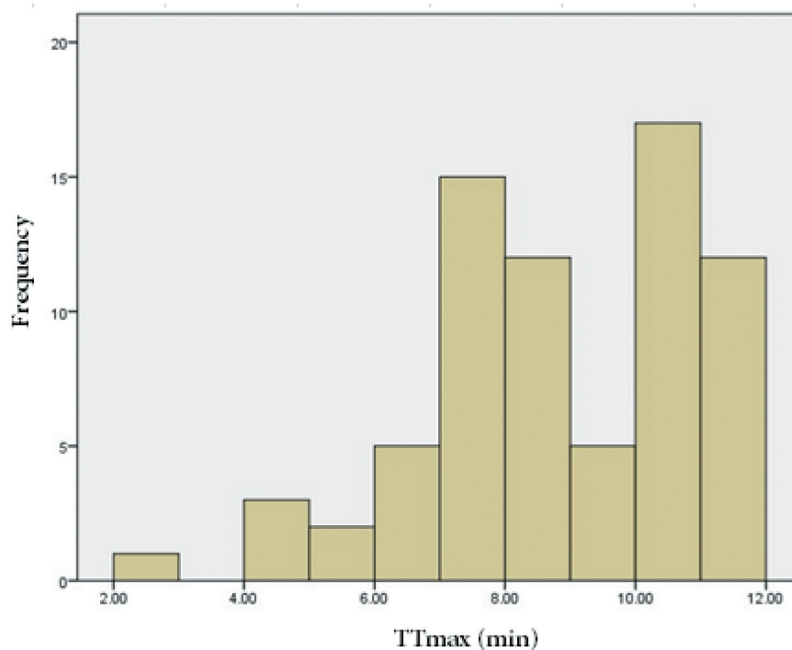
Figure 18. Frequency of TT_{max} distribution (with maximum TT_{max} of 12 min) in TAZs of pattern 2 selected for having distances of less than 4 km from at least one of the three closest parks.

for data of pattern 2, TAZs are divided in two accepted and rejected classes respectively for having TT_{max} of less than (or equal to) and more than 12 min. Results of the examination of the frequency of TT_{max} of these two classes as presented in Figures 18 and 19 show the validity of this classification. As can be seen, the maximum and minimum values of TT_{max} in the two selected and rejected classes are respectively 12 and 8 min. The range of TT_{max} for the selected class is between 2 to 12 min, which is in perfect agreement with the objectives of having a maximum TT of fewer

than 12 min. However, due to the high variability of TT_{max}, ignoring the second minor pattern with a gentle slope in Figure 17, and considering the maximum values of TT_{max} in model fitting, a number of TAZs with TT_{max} lower than 12 min are included in the rejected class, leading to some omission errors. The range of TT_{max} for this class varies between 8 to 55 min with the maximum frequency being located in 14–17 min, which is higher than the threshold value of 12 min (Figure 19). Rejected class includes 97 TAZs, from which TT_{max} of 17 TAZs are less than 12 min
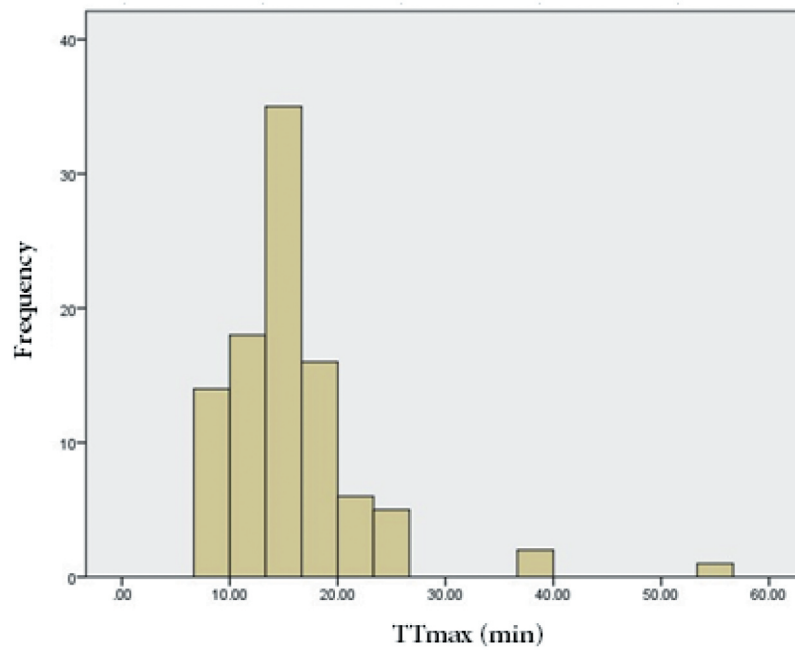
Figure 19. Frequency of TT_{max} distribution (with minimum TT_{max} of 8 min) in TAZs of pattern 2 selected for having distances of more than 4 km from the three closest parks.

(8–12 min), which shows an accuracy of 82%. However, because of the importance of the accepted class and lack of commission errors (accepting *TTs* that are higher than the management aim) in this selection, the fitted model of distance-time relations can be capable of a useful tool for equity management and planning.

5. Conclusions

In this paper, the traffic-related dynamics of *TTs* in relation to the problem of inequity of access to the three closest urban parks in the Tehran megacity is analyzed. Traffic maps of the area at five different times of a working day are used to define *TTs*. Relations between the *TT* and the network distances from TAZs to the three closest urban parks are modeled. Results show positive relations between the *TT* and the distance in all five-time samples. At the same time, an increase of distance leads to an increase of the *VTTs* leading to different *TTs* of locations with similar distances to the closest service centers. The prime reason for this increase may be related to the increase of the diversity of access roads and traffic conditions in longer distances. However, the increase rate of the *VTT* is higher in peak traffic times (at 7 a.m. and 6 p.m. in this study). This means that TAZs within the same distance from their closest parks have to spend unequal times to access a park. Results show that the Gini coefficient of accessibility to the three closest parks shows considerable variation at different times of the day. Assuming people are interested in minimizing the required *TTs* to their three closest parks,

then they have to choose different times, and there will be inequities between residents in their best times to visit parks. Those areas with low distance, low *TTs*, and low *VTTs* to a park would have more temporal opportunities to visit a park, whereas residents with higher *TTs* and *VTTs* for a park would have limited temporal opportunities to visit parks. As an example, the results of this study show that the best and worst times to visit parks in the study area coincide with the traffic conditions and respectively include 12 p.m. (low traffic time) and 6 p.m. (high traffic congestion time). Although inequities of time choice may be less important with a visit to a park, it would be more important in other cases where time choice is limited. An example is when one has to attend school at a certain time or when there is an urgent and instant need for the services of a health center or a hospital.

Because of the focus of this research on the examination of traffic-related *TTs* and distance relationships, access to parks has been based on driving either by private or public cars. Although this may not be valid for areas located in closer distances to parks because of the irregular distribution of parks, and high variation of access distances (in some areas up to 18 km), traveling to parks by driving is a normal practice in the study area. In addition, driving by car is the only access choice for children, elderlies, and people with disabilities. In reality, a combination of different transportation modes is used, and traffic plays a more important role in longer distances. This is in agreement with the findings of this research that longer distances coincide with higher values of *VTT*, where travel by car is the preferred transportation

type. Samples of traffic conditions have been limited to five times in a few working days, which may not well represent the dynamics of traffic conditions. In this research, *TTs* and *VTTs* in three routes from each TAZ to the 3 closest service centers, defined by the minimum network distance concept, are studied. In practice, a collection of alternative routes from each TAZ to a given service center may be considered, and the one with the minimum *TT* will be preferred. Due to the complexities of considering variable routes from each place to a given destination and the resulting spatial inequities, a single shortest route for each origin and destination is used in this research. However, for the reduction of the limitations caused by considering only a single route and destination, three routes and destinations for each TAZ are used and the temporal dynamics of their *TTs* are evaluated. Although consideration of alternative routes for minimizing the *TTs* may lead to a reduction of the *VTTs* and compensation of some highlighted inequities in this research, this does not undermine the important role of time and distance relations in the variability of access inequities. Evaluation of temporal dynamics of spatial inequalities under variable routes and traffic conditions is an important problem, which is the subject of our continuing research.

Method and concepts of distance and traffic-related inequities of accessibility developed in this research can be adopted for inequity studies in other geographic areas and public service centers. The education and health-related centers in particular, have temporal inequities in accessibility that can lead to major discriminations and impacts among residents. Assessment of relations between the temporal and distance-based inequity of accessibility to urban services reveals new knowledge and information which can be useful for more precise and realistic spatial equity assessment and more effective spatial planning. Results indicated a significant relationship between the distance, *TT* and *VTT*. These relations can help urban planners to reconsider the traffic congestion impacts on access equity in their decisions and planning. In a way that, by defining the relationship between the access distance, *TT*, and *VTT* at different times of the day, urban planners can analyze and manage both the spatial and temporal inequity problems. As an example, an examination of the inequity of travel time in the Tehran megacity shows that maximum *TTs* from TAZs to the closest parks show high variability ranging from 1 to about 55 min. By using the developed linear model between the TT_{max} and distance, to decrease the maximum *TT* of TAZs to their closest park to less than 12 min, the maximum distance of TAZs to the closest parks should be less than 4 km. These results can be used to map and identify the deprived TAZs as well as to highlight the prime priority areas for the establishment of new parks.

In ideal situations of equity, equal *TTs* with zero variations may be assumed. But in practice, inequity is part of the real-life, and its minimization or control using existing standards is the key objective. Therefore, minimizing differences of *TTs* and their variations provides a more realistic model for the management of the inequity. Strong relations observed between the distance, *TTs* and *VTTs* show how inequity of distance leads to temporal inequities, how spatial inequity plays a key role in the management of inequity, and finally how temporal inequity can be controlled by reducing the spatial inequities. As an example, statistical models of interactions between the distance, *TT*, and *VTT* as developed in this research can be used to define the maximum acceptable accessibility distances to different service centers in varying geographic regions. Such that inequities of *TTs* between residents in different or equal distances from the closest service centers are reduced to a standard or maximum acceptable level.

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Data availability statement

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