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CHALLENGES AND SOLUTIONS

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AN ANALYSIS OF PUBLIC TRANSIT CONNECTIVITY INDEX IN TEHRAN

CASE STUDY: TEHRAN MULTI-MODAL TRANSIT NETWORK

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ABSTRACT

Public transit is a major priority in modern management of large cities and metropolitan areas in particular. Public transit systems in such cities consist of a large number of nodes and lines which a station (node) is a bridge between the people and the public transit network, based on which the concept of input and output connectivity power for each station can be defined. The objective of this study is the application of the transit connectivity indices to the multimodal transit network in the city of Tehran. The public transit network data employed in this study were taken from the Tehran Traffic Control Company, and Tehran Urban and Suburban Railway Operation Company. The methodology for measuring transit connectivity consists of three measures: Node connectivity, Line connectivity and Regional connectivity, where activity density is applied to these measures. The results of node connectivity analysis shows that most of the node connectivity in concentrated in the city center with many nodes in the center along routes going north and south. Line connectivity analysis shows that there is a concentration of highly connected lines that are near Tehran municipality regions 12 and 16. Finally, we find that areas with more metro and bus facilities with respect to other areas have a better regional connectivity. One of these areas includes Sadeghiyeh Metro Station which is the junction of Tehran Metro Line 2 and Tehran Metro Line 5 which have a high connectivity power. The results of this study can be used to suggest some ideas on how future investments in rail and bus should be prioritized. Particularly in Transit-Oriented Development (TOD) and sustainable development projects, urban planners can design transit stations with high performance to access crucial services in poor areas. Furthermore, a transit network modeling to develop connectivity indices with other transit factors and the relation between connectivity measures and TOD indices can be evaluated in future research.

KEYWORDS:
Public transit, connectivity indices, TOD, complex network.

1 INTRODUCTION

Public transit is a major priority in modern management of large cities and metropolitan areas in particular, due to features such as high efficiency in the use of transport inputs and alignment with sustainable development (Hadas et al., 2011).

Generally, transit users choose a service because of two reasons (Sarker et al., 2014).

- Service quality: such as walking distance, in-vehicle travel time, waiting time, number of destinations served and number of transfers needed to reach final destinations, etc. If all of these factors are taken into account, measuring transit connectivity becomes a multidimensional problem.
- Multiple routes of a transit system: To establish transit system connectivity, it is necessary to determine the extent of route integration and coordination within the network. In this context, connectivity can be used as one of the indicators measures to quantify and assess transit efficiency and performance effectively.

A public transit system consists of nodes and lines which are represented by a complex network of spatial and temporal data. The nodes are termed stops and the lines are termed links. Links in a multimodal transit network have different features from those in a road network. While a link in a road network is a physical part that connects one node to another, a link in a multi-modal transit network is part of transit line that serves a sub-sequence of transit stops (nodes). On the other hand, a stop can be served by different transit lines, and there may be multiple transit links between nodes in a multi-modal transit network. However, on a highway network there is only one link between two nodes (Mishra et al., 2012). Predominantly, a public transit station is a bridge between the people and the public transportation system. Based on this, for each station and each line passing through it, the concept of input and output power is defined by Mishra et al. (2012). The connectivity power for each station including the quality of transit services provided by the station contains fleet capacity, frequency and speed, and activity density around the station (Mishra et al., 2012; Kaplan et al., 2014). Hence the connectivity index can be defined as the summation of output and input connectivity power.

Measures of transit connectivity can be useful for transportation planning agencies in several ways. First, connectivity can be used as a performance indicator for transit stops and/or routes in order to evaluate the overall system performance, allowing public agencies to rationalize public spending in transit accordingly. Second, in rural or suburban areas, where detailed information regarding transit ridership is not available, connectivity can be translated into a measure of performance for developing service delivery strategies. Third, the connectivity measure can assess effectiveness and efficiency of a transit system to prioritize the nodes/links in a transit system, particularly in terms of emergency evacuation. Finally, transit connectivity measures offer transit users the potential to assess the quality of transit service (Welch, 2013).

In other words, the rapid growth of metropolises with increasing populations has created several problems such as traffic and disorder in the urban transportation system. These problems were the main challenges facing urban planning in the late twentieth century that affected the achievement of the goals of sustainable urban development. On the other hand, the increase in motorized transportation and large use of it in cities has caused problems such as severe environmental pollution, traffic congestion, residents' time loss, excessive consumption of energy, insecurity of roads and accidents (Vafa-Arani, 2014). Therefore, life is difficult in these environments and welfare has been reduced. Tehran is also experiencing such issues. The bus rapid transport[1] system along with the development of the Metro system has been adopted in the form of the public transit development policy in Tehran to facilitate public transit and tackle these problems (Taleai et al., 2014).

At the same time, accessibility and extensible land are applied to land use models, especially residential land. However, development of the remaining land in Tehran has been in decline in all 22 districts. It can be expected

[1] BRT

that connectivity as an indicator of transit accessibility is considered the only - main - factor of land use and TOD modeling (Lotfi and Koohsari, 2009). Due to the need for an integrated view in the field of design, planning and implementation of transport and land use policies in metropolises such as Tehran, these indices can be considered essential for establishing relationship between these two fields of urban management. Hence in this paper, public transit connectivity and its concept has been discussed as a bridge between transportation planning and land use (Mishra et al., 2012).

In the city of Tehran, urban managers offer multiple solutions. The most important among these solutions might be evaluation of performance for public transit network. One of the transit performance indicators is connectivity power of stations and lines.

The objective of this research is application of the transit connectivity index provided by Mishra et al. (2012) to the multimodal transit network in the city of Tehran, and its use in order to propose policies for the improvement of city planning in line with transit-oriented development. To compute this index, we rely on a graph theory approach that determines multimodal transit network performance by quantifying measures of connectivity in three steps: node, line and regional connectivity.

The paper is structured as follows. Section 2 introduces the literature review, followed by the methodology section introducing transit connectivity indices (node, line and regional connectivity measures) applied in this study and a description of the study area. Section 4 presents the multi-modal public transit network data for the city of Tehran including Metro, BRT and Bus, followed by section 5 which is dedicated to the findings and results of the study. Section 6 concludes the paper with the final and most important conclusions of the study.

2 LITERATURE REVIEW

Public transit is a connector between people and essential needs of life such as jobs, education and shopping. Urban travelers are concerned with distance between people and public transport stops (level of accessibility) and the mobility of public transportation services, whereby mobility is defined as the ability to travel and accessibility can be measured by the length of a journey from one's house to work with public transit (Sanchez et al., 2004). The most common method of measuring mobility is to evaluate the frequency of a service at a particular node. Thus connectivity helps expand performance to meet the demands of multimodal transportation systems (Hadas et al., 2011). Cheng and Chen (2015) showed that connectivity and accessibility are key related concepts, so that connectivity means the linkage among regions and centers of activity, and accessibility addresses the ability of people to reach destinations by different modes of transportation. Therefore, connectivity is a major indicator of people's access to the multi-modal transportation network. After this study, Papa and Bertolini (2015) proved that rail-based accessibility is higher in urban areas where inhabitants and jobs are more concentrated around the railway network and in lesser measure in urban areas with higher values of network connectivity. In the literature, there are different approaches to define and quantify the concept of connectivity. Broadly, connectivity measures have been investigated in the field of social network and graph theory. However, their application to public transit is confined. The first measure is degree of centrality which has been defined as the sum of graph-theoretic distances from all other nodes, where the distance from one node to another is defined as the length of the shortest path from one to the other (Freeman, 1978). Based on this, nodes with low nearness grades have short distances from others, and will tend to be more accessible. In topology and related fields of mathematics, nearness is a widely used concept and one of the basic elements of relationship in a topological space. Another form of centrality commonly used in the literature is betweenness centrality which can be defined as the share of times that a node relies on another node to reach a third node via the shortest path. In other words, betweenness centrality essentially counts the number of geodesic paths that pass through a node (Mishra et al., 2012). This approach is developed by Sarker et al. (2014) for multimodal transit network.

For multimodal transit networks, Park and Kang (2011) demonstrated transit characteristics when measuring the connectivity index of a node. Two years later, Hadas (2013) presented a unified methodology for extracting, storing and analyzing public transit data as derived from different public transit systems using spatial analysis based on Google Transit data in which network coverage level, average speed, intersection coverage level, stop transfer potential and route overlap were used as connectivity indicators for comparison. This method authorizes partly new spatial and temporal planning with GIS methods that use the topological, geometric, or geographic attributes that characterize an entity.

In recent years, Ceder (2007, 2009, 2010 and 2014) has applied the transit connectivity measure for different cities, and has quantified it for a set of multiple and feasible transit paths for each origin-destination pair, including the three shortest paths and the three most popular paths to account for the probabilistic nature of transit path choice. Furthermore, he constructed a set of both quantitative and qualitative attributes that represent the spatial, temporal, information, and capacity factors; the common denominator for all transit services is the quality of the following connectivity attributes: average walk time, variance of walk time, average wait time, variance of wait time, average travel time, variance of travel time, average scheduled headway, variance of scheduled headway, smoothness (ease) of transfer, availability of easy-to-observe and easy-to-use information channels, and overall intra- and inter-agency connectivity satisfaction.

Mishra et al. (2012) proposed the measures to determine connectivity from a graph theoretical approach for all levels of transit service coverage integrating routes, schedules, socioeconomic, demographic and spatial activity patterns. They introduced the aim of using connectivity as an index to survey and evaluate transit service in the following fields: prioritizing transit locations for funding; providing service transfer strategies, especially for areas with large multi-jurisdictional, multi-modal transit networks; providing an indicator of multi-level transit capacity for planning objectives; evaluating the effectiveness and efficiency for node/stop prioritization; and making a user friendly tool to determine locations with higher connectivity while choosing transit as a mode of travel.

Recently Sarker et al. (2014) developed a new methodology to measure transit connectivity that does not require detailed socio-economic, demographic, transit ridership data and transit assignment models. In this research, the methodology incorporates a graph theory approach to assess the performance of large-scale multimodal transit networks by quantifying indicators of connectivity at multifold levels including transit stops, links and lines. It also considers the unique qualities of each transit line and stop, as well as their accessibility when developing a single connectivity index.

A review of previous studies and the research gap in the field of public transit connectivity measures shows that the main factors of public transit network and land use are not synthesized for measuring this index. The present paper therefore aimed to evaluate the connectivity index as a new approach to the relationship between transportation planning, land use and TOD.

3 METHODOLOGY

The connectivity index is derived from graph theory approach, where a measure of transit connectivity was proposed by Mishra et al. (2012) to determine multiple lines per origin–destination pair in the complex multimodal network. In other words, this index measures the degree of connection to each node in the multi-modal public transport network.

In this study, the methodology for measuring transit connectivity consists of three steps: (i) Node connectivity: calculation of inbound and outbound connecting power of transit or service level at stations (nodes), (ii) Line connectivity: The total connecting power of a line is the sum of the averages of inbound and outbound connecting powers for all transit nodes on the line, and (iii) Regional connectivity: The summation of the connectivity of all nodes within that area scaled by the number of nodes.

In the first step, the inbound and outbound connecting power of transit for each node is defined as (Mishra et al., 2012):

$$P_{l,n}^{o} = \alpha(C_l \times \frac{60}{F_l} \times H_l) \times \beta V_l \times \gamma D_{l,n}^{o} \times \vartheta A_{l,n} \times \varphi T_{l,n}$$
$$P_{l,n}^{i} = \alpha(C_l \times \frac{60}{F_l} \times H_l) \times \beta V_l \times \gamma D_{l,n}^{o} \times \vartheta A_{l,n} \times \varphi T_{l,n}$$

where C_l is the average vehicle capacity of line l, F_l is the frequency of each operating line l (60 is divided by F_l to determine the number of operations per hour), H_l is the daily hours of operation of line l, V_l is the speed of line l, and $D_{l,n}^{o}$ is the distance of line l from node n to the destination. The parameter α is the scaling factor coefficient for capacity, which is the reciprocal of the average capacity of the system multiplied by the average number of daily operations of each line, β is the scaling factor coefficient for speed, represented by the reciprocal of the average speed on each line, and γ is the scaling factor coefficient for distance, which is the reciprocal of the average network-route distance.

The inbound and outbound connecting power considers activity density of a transit line l at node n, which represents the ambient urban development pattern in which the transit line is situated, based on both land use and transportation characteristics. The development pattern reflects the land use activity in a particular region which can be captured by the number of households, employment, spatial distribution of activities and facilities in that area. Mishra et al. (2012) defined activity density in a number of ways. In this paper the activity density is set equal to the ratio of households and employment in a zone to the unit area. Operationally, this could be extended to cover particular urban structures or compositions of interest, to account for metrics of sprawl, walkability etc. Hence activity density is defined as:

$$A_{l,n} = \frac{H_{l,n}^{z} + E_{l,n}^{z}}{\Theta_{l,n}^{z}}$$
$$T_{l,n} = \frac{\sum P_{l,n}^{t}}{\Theta_{l}^{z}}$$

where, $A_{l,n}$ is activity density and $T_{l,n}$ is a transfer-scaled index. Also, $H_{l,n}^{z}$ is the number of households in zone z containing line l and node n, $E_{l,n}^{z}$ is employment for zone z containing line l and node n, $P_{l,n}^{t}$ is the total connecting power of line l at node n; Θ_{l}^{z} is the number of lines l at node n.

In the two steps, the line connectivity can be defined as follows:

$$\theta_l = \frac{1}{|S_l| - 1} \sum P_{l,n}^{t}$$

where, S_l is the set of stops in line l.

And in the last step, the regional connectivity index equation is defined as:

$$\theta_R = \frac{1}{|S_R| - 1} \sum P_{l,n}^{t}$$

where, S_R is the set of stops in region R.

3.1 STUDY AREA

Tehran, the capital city of Iran, is geographically located at approximately 35° 45' N and 51°24' E. The area of Tehran is about 776.96 km^2. This city is divided administratively into 22 regions and 123 districts and 374 neighborhoods (Statistical Yearbook of Tehran, 2014).

According to the Census of the Iran Statistics Center in 2011, Tehran has a population of 8,154,051 and 2,597,731 households compared to 2006. In addition, the average population growth is 3.1 in Tehran after ordinary households compared to 2004 (General Population and Housing Census, 2011). Population for the different 22 regions as of 2015 is shown in Fig. 1. As can be seen in this figure, districts 2, 4, 5 and 15 have the highest population. Thus it can be said that these districts produce the most trips.

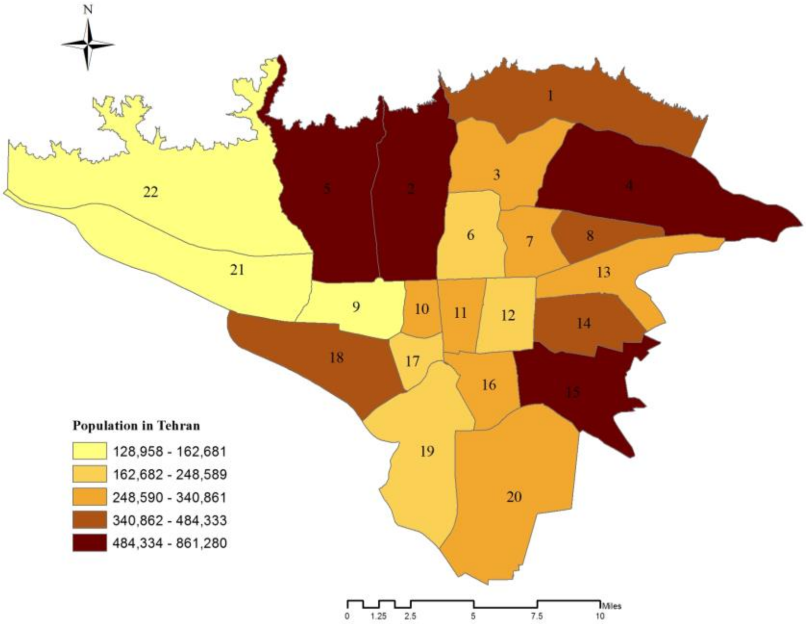

Fig. 1 Population of the 22 municipality districts of Tehran city in 2015

3.2 THE URBAN CONTEXT

An efficient public transport system is critical for developed countries. However, the cities in developing countries are typically characterized by high-density urban areas and poor public transport, as well as control of land use, resulting in pollution, congestion, and a host of other transportation problems. Generally, public transport planning and management is relevant and suitable for developing countries, addresses current transportation system inefficiencies, explores the relationship between mobility and accessibility, and analyzes the results for future use (Verma and Ramanayya, 2014). As one of the developing world's major cities, Tehran has been active over the last few years in the field of transportation infrastructures, including the metro and BRT network.

Tehran Municipality is currently organized as a mono-centric city with a major CBD (districts 6, 7, 11 and 12) where most commercial activities are concentrated. This is surrounded by several residential areas. Therefore, districts 6, 7, 11 and 12 attract the most trips in Tehran, because of the higher land use characteristics. In Tehran, most of the future urban development is anticipated to be accomplished in the north and eastern divisions of the city with lower levels of development in the south of the city (and districts 21 and 22) for decentralization (Allen, 2013).

Tehran's bus system has a huge network of buses, trolleybuses and Bus Rapid Transit (BRT) (Tehran Municipality Statistics, 2013).

- The Tehran Bus Company is one of the Subsets of Tehran Municipality, and it has been established since the 1920s. This company started operations with 246 buses and 5 lines of 30.6 kilometers at 1955. However, 150,000 travelers are carried daily by them, but the quality of both services and vehicles was weak at the end of the twentieth century.
- Tehran Bus Rapid Transit was founded to change attitudes and cause great upheavals in the structure of transport management and urban traffic. Typically, it is a symbol of the application of science and technology in operation to address Tehran's issues. BRT was officially started in 2008. In that time, Tehran BRT had three lines with 60 stations in different areas of the city. As of 2011, BRT had a network of lines with 100 kilometers (62 miles) which carried 1.8 million passengers daily. However,

the proper context of this massive project is applied integrated management and inter-agency coordination between operating organizations and agencies in the field of urban management.

Tehran Metro is called a set of Tehran urban trains and "Tehran Urban and Suburban Railway Company". Planning of the construction of Tehran's Metro started in the 1970s. The first two of the eight projected metro lines were started in 2001. This system consists of four operational lines, with construction beginning on a further two lines in 2007. As of 2014, 815 million trips were made on Tehran Metro. In 2015, the total system was developed to be 110 miles long. It is planned to have a length of 270 mi with 9 lines once all construction is complete by 2028. This service runs trains from approximately 05:30 to 23:00 all days of the week, and carries daily more than 3 million passengers (Statistics of Tehran Urban and Suburban Railway Company, 2015).

Generally for Tehran public transit, the metro is defined as a first layer of a multimodal public transit system, and the BRT network consists of 10 high speed lines as the second layer. However, it will be required to develop both qualitatively and quantitatively.

3.3 MODAL SHARE

Every day in Tehran about 18 million trips are undertaken, chiefly with specific objectives. Trip purposes may be divided into four groups, including work, education, shopping and leisure trips (Tehran Municipality, 2014). In the meantime, it is necessary to become acquainted with the number of trips attracted and produced from anywhere in the city to recognize and appropriate transportation planning. In 22 districts of Tehran at 2011, the number of trips produced and attracted are 6,799,911 and 6,799,906 (Tehran Municipality Statistics, 2012). Also, 22 % of trips are made by bus, 23 % by shared taxi, ten per cent by metro, ten per cent by minibus, seven per cent walking and cycling and the rest by private car (28 %). These vehicles were responsible for 88 % of local air pollution annually (Hashemi, 2010).

3.4 DEVELOPING A VISION AND STRATEGY FOR THE TEHRAN PLAN

Tehran Municipality worked hard to develop a visionary strategic plan for transport ‘Tehran in 2025’ during a five year period (2003–2008). This comprehensive plan is based on the wider ‘Tehran’s Comprehensive Strategic Development Plan – 2025 Outlook’. By 2025 Tehran’s road would be handling some 25,388,000 daily trips. However, if this was to be achieved, it was perfectly obvious that the mass transit options had to be seriously improved. Indeed, in the chosen scenario, public and semipublic actors provided the variety of collective transport needed for a 75 per cent modal share. The backbone of this system would require a dense, high capacity multimodal public transport network (Allen, 2013).

Tab. 1 shows the number of trips required if the ambitious target of 70 percent modal share of trips made by mass transit were to be achieved by the year 2025.

System	Mode	Trips frequency	Trips share (%)
Private	Cars and lorries (LDV and HDV)	3,960,000	22
	Motorcycles	540,000	2
Public	Urban railway	8,100,000	30
	Urban bus	9,036,000	32
	Minibus and vans	2,402,000	8
Semi-public	Taxis all types	1,350,000	5
Total		25,388,000	100

Tab. 1 Modal predicted share of trips by mass transit in 2025 (Tehran Municipality, 2009)

Based on Tab. 1, urban rail and urban bus will have the most trips. Hence, the largest budgets should be allocated to these modes in strategic development. Therefore urban rail and bus networks should be designed with proper planning as regards stations and lines, so that these stations and lines create a public transit network with the best performance. One of the public transit network performance indices is the connectivity index.

4 MULTI-MODAL PUBLIC TRANSIT NETWORK DATA

In this study, Tehran was selected according to the multi-modal public transit network and traffic crisis. The public transit network data employed in this study were taken from the Tehran Traffic Control Company, and the Tehran Urban and Suburban Railway Operation Company. These data include the stations and lines (Bus, BRT and Metro) for different regions and areas of Tehran municipality.

4.1 BUS AND BRT NETWORK IN TEHRAN

Based on the database received from the Tehran Traffic Control Company (public transit sector), the bus and BRT network has 463 sweep lines and 4750 stations at 2015, so that a 6500 bus fleet is active in this network. This database was classified by nine fields such as bus speed and driver code. The data show that 4.5 million people are displaced by buses throughout a day in Tehran, and the bus share of daily mobility is about 20 percent in Tehran. In this study, due to the high volume of the bus database, data were extracted from one day on 05/11/2015[2]. For this day and after filtering there were 5,420,623 records for each bus (based on the bus driver code), and 5342 active buses. This database was analyzed by SQL Server 2014 software. The bus network coverage consists of stations and lines as shown in Fig. 2. As can be seen from Fig. 2, most of the node connectivity is concentrated at the city center with many nodes.

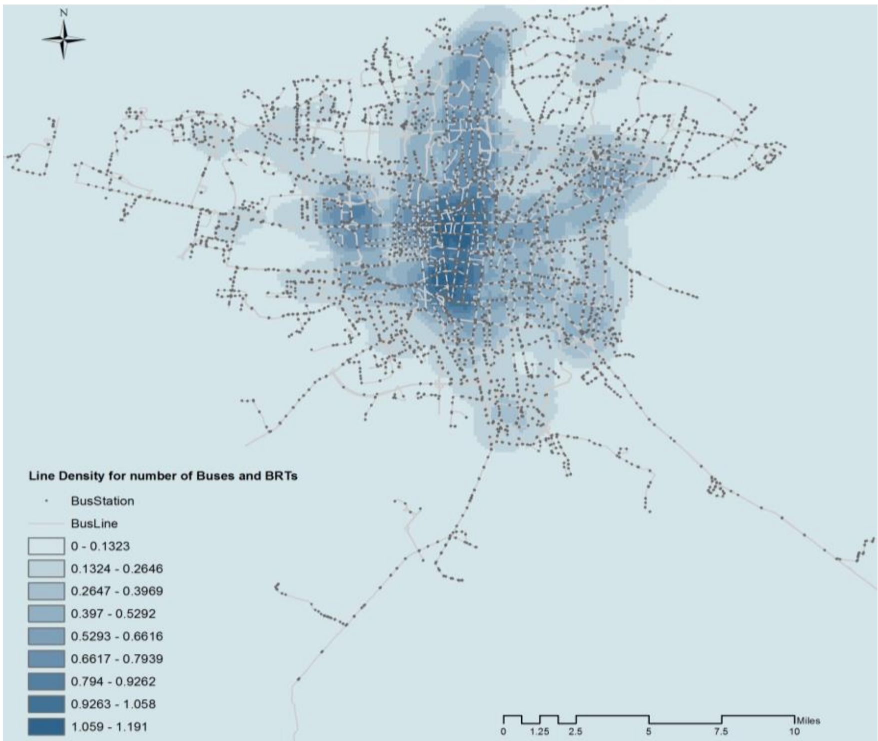

Fig. 2 Bus lines coverage by the number of buses in Tehran Bus network

[2] This day was Monday, a mid-week day, because of public transit usage and travel behavior in Tehran. In addition, the day was not a public holiday.

4.2 URBAN RAIL NETWORK IN TEHRAN

Tehran Metro is concerned as a strategy to improve the traffic in Tehran. However, the ability to take advantage of public transit is not considered in its planning. Such lack of attention to the dimensions of this approach in building subway stations means that large groups of people are denied access to the metro network of Tehran. Tehran metro has an average daily travel demand of more than two million passengers, with low fares being paid by travelers.

According to statistical analysis of the current situation, the current metro trains are active on lines 1, 2, 3, 4 and 5 throughout the 183-kilometer line. In this study, Tehran Metro network data have been collected by Tehran Urban and Suburban Railway Operation Company, the database includes performance information and reports of passenger trips. Tab. 2 shows information on Tehran and Suburban metro lines operating at 2015. Line 2 in Tehran Metro network has the highest number of daily ridership and line 5 the lowest.

Line number	Number of daily ridership (ordinary days)	Number of stations	OD travel time (min)	Number of trains
Line 1	398	29	70	29
Line 2	424	22	47	27
Line 3	138	15	55	8
Line 4	322	18	40	17
Line 5	186	10	52	15

Tab. 2 Tehran and suburban metro lines characteristics

Also, trip generation information is shown for each line at different times in a day (Monday, 05/11/2015). Based on Fig. 3, it is clear that Lines 1 and 3 had the highest and the lowest number of trips, respectively. In addition, the peak of trips is between the hours of 7 to 8 and 17 to 18.

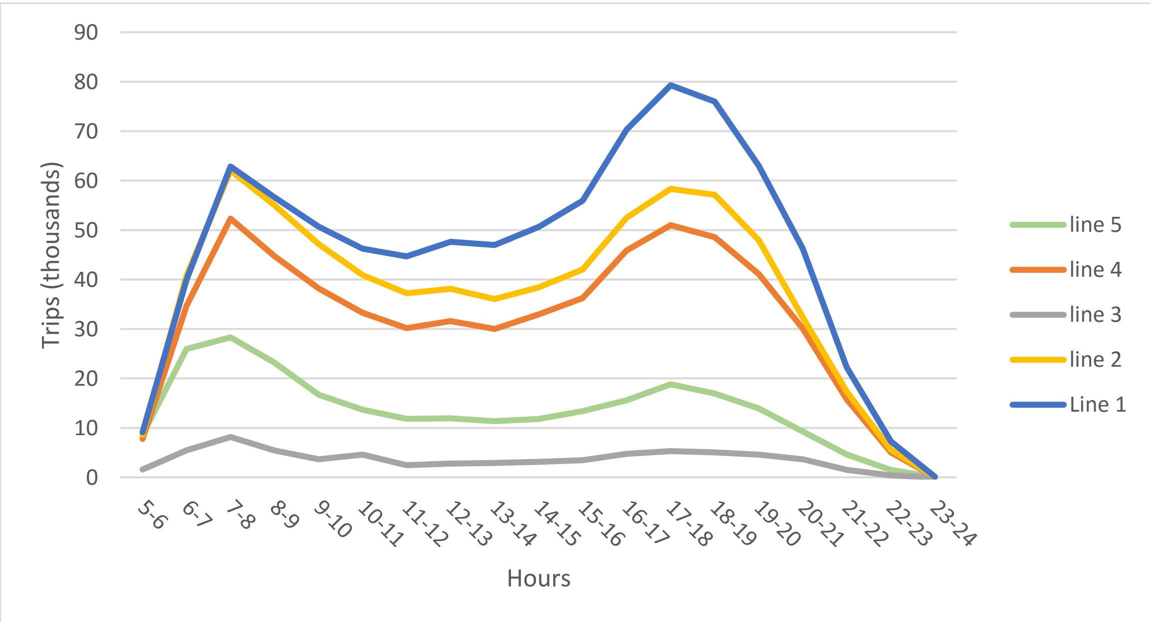

Fig. 3 Number of daily metro passengers by line in Tehran

5 FINDINGS

This section presents the results of the methods described in the previous sections for the multimodal transit network in the city of Tehran. The analysis of transit connectivity in the nodes, lines and regions focuses on the performance factors of transit networks (bus and metro), such as capacity, speed, frequency and distance of buses and metros. Based on section 3, characteristics of the household population and employment are added in the connectivity index. Tab. 3 presents summarized results of regional connectivity measures for the bus and metro networks. Based on these results, the average regional connectivity measure for the bus network is more than the metro network. Therefore, the bus network performs better, based on transit connectivity, than the metro network in Tehran. On the other hand, the standard deviation of this measure for the metro network has a high value, because many areas of Tehran are not covered by metro stations.

Regional connectivity measure	Number of observations (Municipality areas)	Average measure	Standard deviation
Bus network	123	8.43	13.81
Metro network	123	5.03	14.76
The whole public transit network	123	8.01	13.74

Tab. 3 Summary results of the regional connectivity measure

5.1 NODE CONNECTIVITY MEASURE

Tehran's multimodal transit network has many stations, comprising metro, bus and BRT. To measure the node connectivity index, it is calculated for each node (station) due to the modes.

Fig. 4 shows the node connectivity results for the bus and BRT transit network in the city of Tehran at the bus station level. As the map shows, most of the node connectivity in concentrated at the city center with many nodes in the center along routes going north and south, because these nodes are placed on the BRT and bus lines with high frequency and capacity. In general, the highest node connectivity is in area 1 in region 12.

Fig. 5 plots the node connectivity for the metro network. It can be observed that the best connected nodes are concentrated in the city center. The Tehran metro network has five lines and 86 stations, with nine stations connecting the two lines. These stations have the best connectivity on the metro network, because the metro performance factors (capacity, frequency and connected lines) are better than other stations.

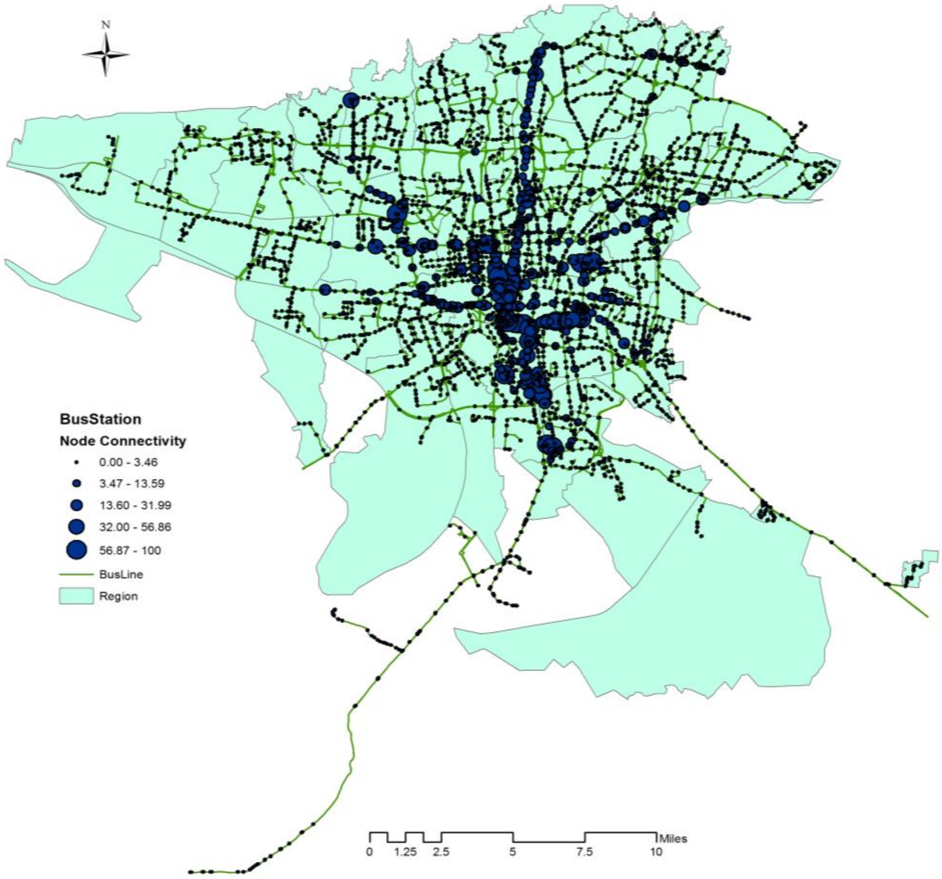

Fig. 4 Node connectivity for the bus and BRT network

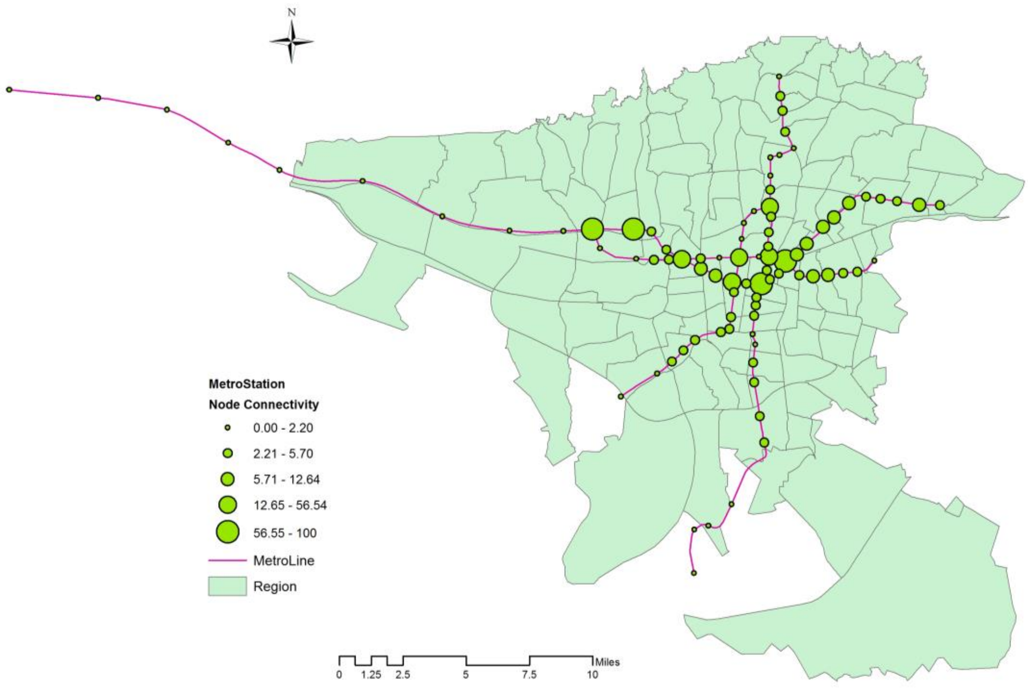

Fig. 5 Node connectivity for the metro network

5.2 LINE CONNECTIVITY MEASURE

In this study, the line connectivity index is applied to the transit network for the city of Tehran. This section provides both metro and bus modes.

Fig. 6 illustrates the line connectivity index for the bus and BRT networks. Because the transit line factors obtained (frequency, speed, capacity and other factors) for western and eastern regions are better than southern and northern regions, line connectivity for these regions (north and south) is higher than in western and eastern regions. The map clearly shows that there is a concentration of highly connected lines that are near regions 12 and 16 because the number of bus and BRT lines in these regions pales in comparison to other regions.

As can be seen from Fig. 7, the best line connectivity measure for the metro lines (87.26) is shown in dark brown (line 4). In contrast to line 4, the measure for line 3 (light yellow) is equal to 16.42, showing that it has the worst line connectivity.

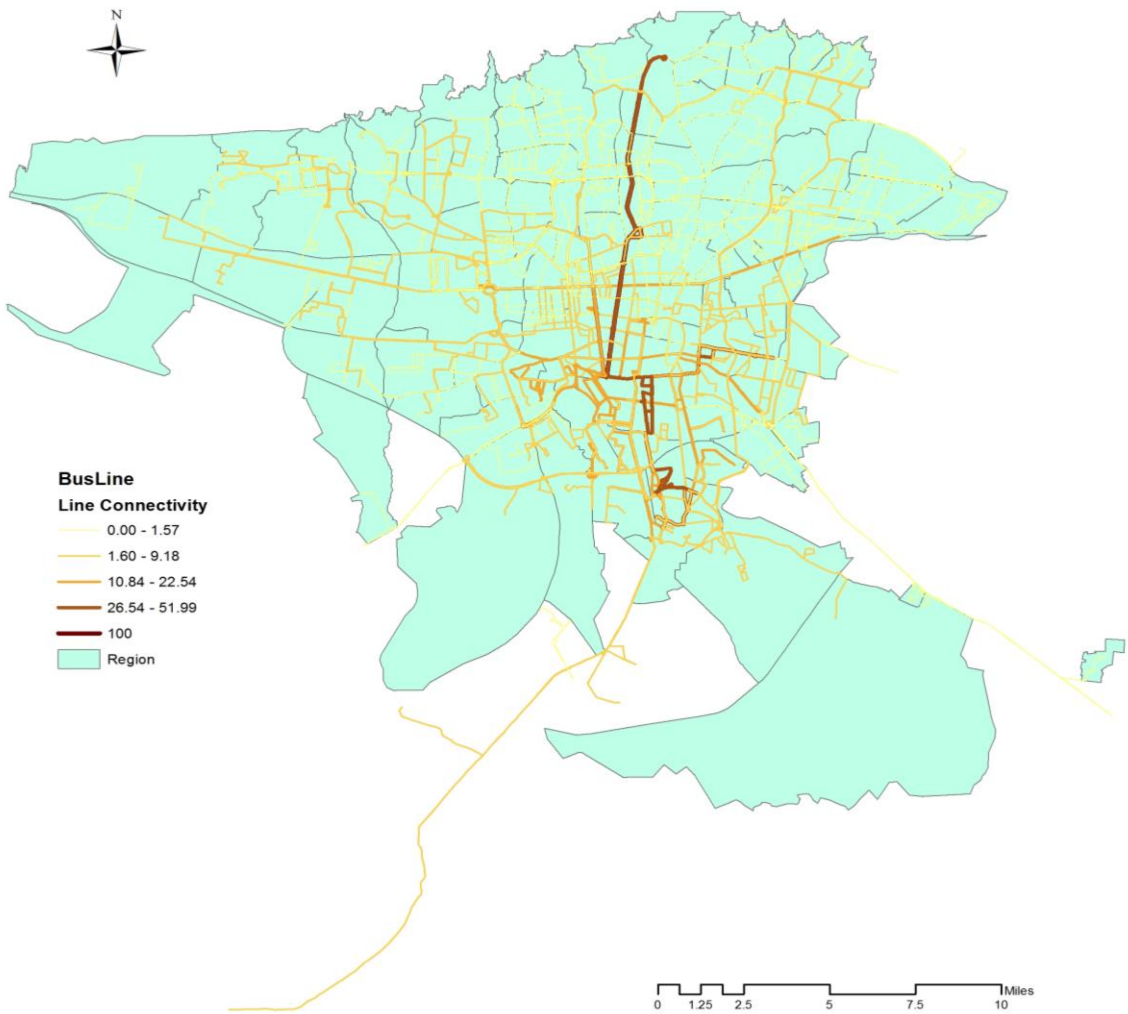

Fig. 6 Line connectivity for bus and BRT networks

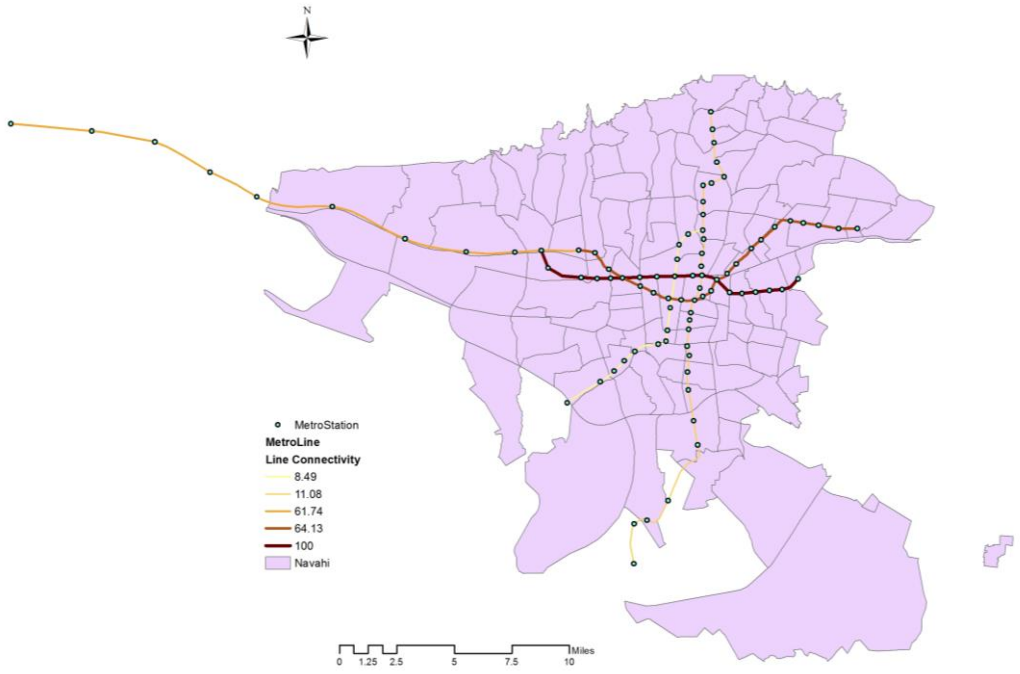

Fig. 7 Line connectivity for the metro network

5.3 REGIONAL CONNECTIVITY MEASURE

Transit connectivity was calculated for each zone within an analysis location. Fig. 8 shows the connectivity of each area for bus and BRT networks. In the figure, areas in dark green have high levels of connectivity under the definition offered in the earlier sections of this paper. As can be seen, areas in light green have very low connectivity. The map clearly shows that areas with major transit services are higher in connectivity. By comparing Fig. 8 with Figs. 5 and 7 it can be seen that due to the high node and line connectivity in bus and BRT networks, the overall connectivity in central areas (a high-performing network) is better than in other areas of Tehran.

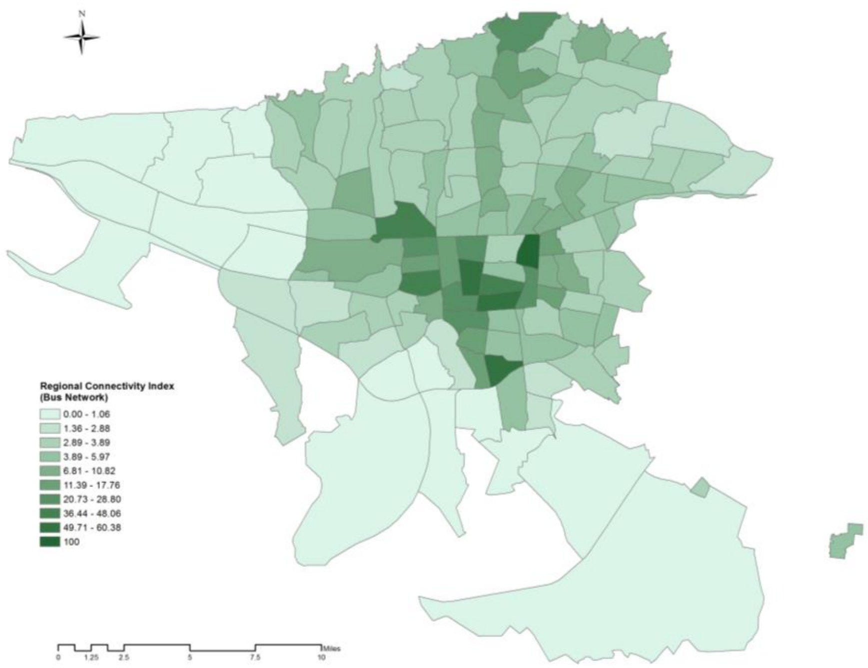

Fig. 8 Regional Connectivity for Bus and BRT Network

Fig. 9 plots the regional connectivity for the Tehran Metro network. As can be seen from Fig. 9, connected areas from North to South and East to West in the city of Tehran have better connectivity than other areas. According to Fig. 6 and 8 it can be seen that the Tehran Metro network just to be covered these areas. It is clear from Fig. 9 that the areas in dark green are better connected because the stations located in these areas connect two high-performing lines.

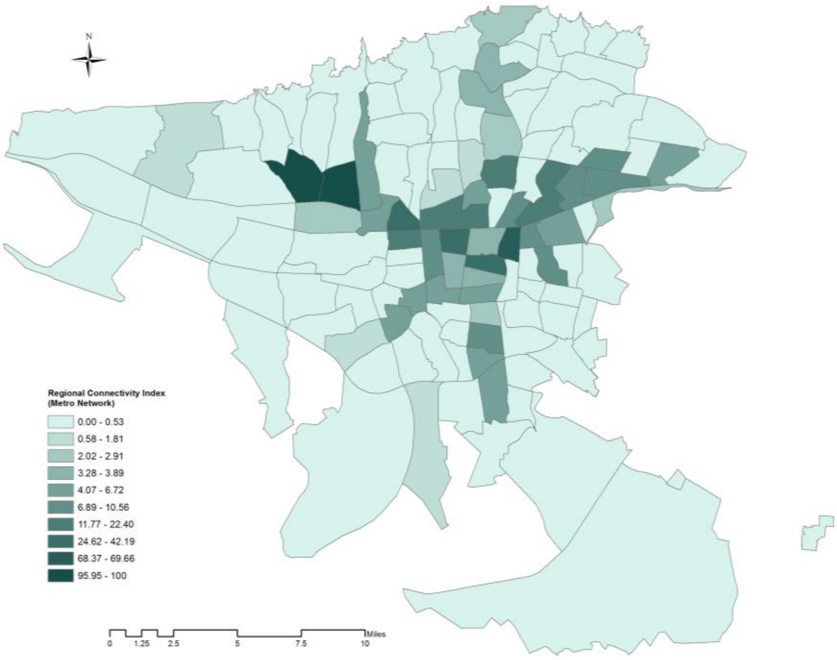

Fig. 9 Regional Connectivity for Metro Network

Finally, by combining the regional connectivity for metro and bus, we reached the total connectivity for each area. Fig. 10 displays total connectivity of public transit in Tehran areas. Based on Fig. 10, we find that areas where there are metro and bus with respect to other areas have better connectivity. Generally, Fig. 10 is a combination of Fig. 8 and Fig. 9.

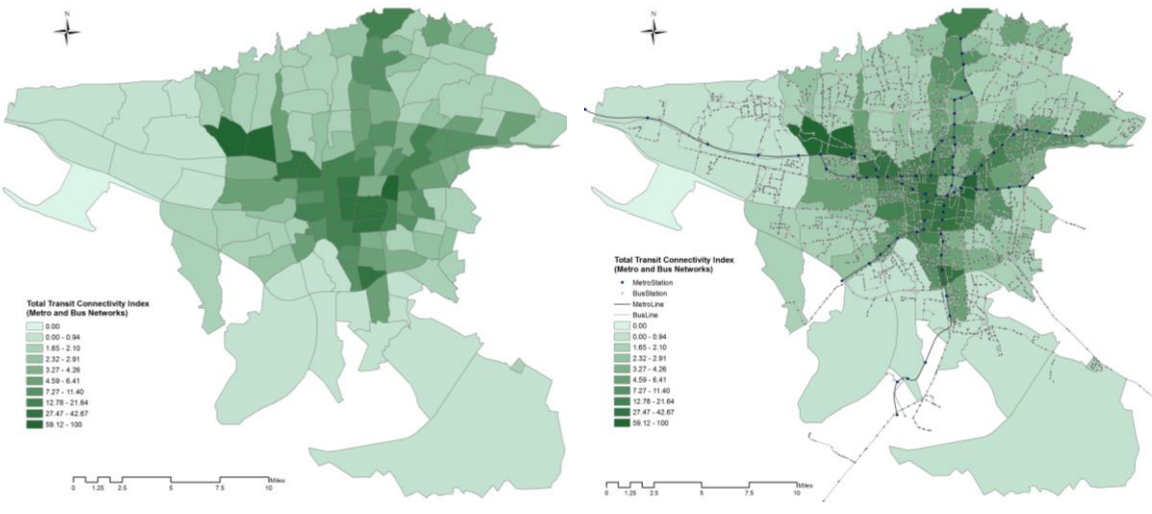

Fig. 10 Total regional connectivity for multi-modal transit network (Metro and Bus)

In Fig. 10, dark green areas have the highest connectivity. One of these areas includes the Sadeghiyeh Metro Station. Sadeghiyeh lies at the junction of Tehran Metro Line 2 and Tehran Metro Line 5, lines which have high connectivity. It is located in the vicinity of the Mohammad Ali Jenah Expressway and Tehran-Karaj Freeway at the western end of Line 2 and eastern end of Line 5. The next station in Line 2 is Tarasht and the next station in Line 5 is Ekbatan. It also has a wide parking area and is considered the most crowded Tehran metro station. Additionally, this station is covered by bus mode.

The results suggest how future investments in rail and bus should be prioritized. The metro has a major role to play in enhancing network performance and, if combined with bus and BRT modes, can provide the areas concerned with high connectivity.

6 DISCUSSION AND CONCLUSION

Recognition of public transit connectivity (supply side) and potential need for this service (demand side) in each municipality area and their distribution are important to transportation planners, because of the crucial role of the public transit system in mass displacement of people and its compliance with sustainable development and social equity (Kaplan et al., 2014). Studies and researches conducted on Tehran indicate a uniform attitude across the public about transit use in the two neighborhoods from one area. The most apparent difference concerns the negative effect of poor accessibility on public transit: the main reason for not using public transportation is "Little accessibility to stations, long distance between the stations" (Masoumi, 2013).

In this regard, this paper examined the public transit connectivity index, which was generated from graph theory as indicated in previous researches. The connectivity index was determined in three steps in the multimodal transit network of Tehran: node connectivity, line connectivity and regional connectivity. The concept of connectivity defined as the level of service such as transit frequency, speed, line distance and capacity is particularly widely used in public transit analysis. The transit network in the city of Tehran includes three modes: BRT, Bus and Metro. The connectivity index is applied by urban form with differences among geographical, land use, highway and trip pattern characteristics between regions.

By calculating nodes and lines connectivity for each area, as well as comparing this index through the population and employment in each area, areas with poor access to services were identified. For areas with low connectivity measures, new lines can be designed to improve connectivity of these areas. Connectivity measures can also be used for identification and improvement of poorly connected areas, Transit-Oriented Development and sustainable development, Based on the weaknesses of the regions/areas in using of public transit services and the severity of this issue, priority of transit projects should be prioritized to be conducted in regions with poorer connectivity.

In this study, Tehran's municipality districts were examined in terms of public transit connectivity, whose results were also exhibited on maps, by integrating the methodology with GIS.

Several policies can be obtained by interpreting and scrutinizing the results as follows:

- In poor areas, urban planners can design bus or/and metro stations with high performance to facilitate comfortable transfers to provide access to crucial services.
- Although there may be many transit stations in an area, connectivity power for this area may be low because of the low level of service for these stations. One of the factors is fleet frequency passing through these stations (waiting time at stations). On the other hand, passengers are usually restless and find delayed buses a big problem; city governments should encourage bus agencies to increase fleet frequency to decrease waiting times.

Sarker et al. (2014) demonstrated that the connectivity measure can assess effectiveness and efficiency of a transit system to prioritize the nodes/links in a transit system. Therefore, the use of a connectivity measure can help urban managers increase efficiency of Tehran's multimodal public transit network (especially the metro network). Additionally, Litman (2015 and 2016) defined efficiency as not being able non-drivers to access education, employment, shopping and recreation. Different factors can affect accessibility such as travel speed and affordability, the quality of transport options, transport network connectivity, land use accessibility, and mobility substitutes such as telecommunications and delivery services. From this perspective, transport systems are most efficient if they increase road network connectivity, support efficient modes, and encourage more accessible land use. This justifies integrated planning that increases transport network connectivity and supports more accessible and multi-modal community development. Based on the results of connectivity calculations in section 5, regional connectivity shows that transit connectivity for suburban areas is very weak. Thereupon, despite of the many transit stations located in this areas, they are highly inefficient. As a result, transit node (station) connectivity can be considered one of the appropriate opportunities for sustainable development and enhancement in urban quality in these areas. In Tehran, this issue is very important in terms of socio-economic inequality and spatial gap between the north, south, east and west of the city. According to the development of public transit systems such as the metro in Tehran, awareness of the efficiency of transit connectivity (especially, node connectivity) on the quality of surrounding environment in the direction of urban planning is essential. The connectivity indices can be used to identify areas with unsuitable infrastructure and to help decision makers for prioritizing areas in development planning and design of urban transit systems. In addition, transit network modeling to develop connectivity indices with other transit factors and the relation between connectivity measures and TOD indices can be evaluated in future research.

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IMAGE SOURCES

Fig. 1: author.

Fig. 2: author.

Fig. 3: author.

Fig. 4: author.

Fig. 5: author.

Fig. 6: author.

Fig. 7: author.

Fig. 8: author.

Fig. 9: author.

Fig. 10: author.

Fig. 11: author.

The cover page: Tehran Municipality, http://tehran.ir

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