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Metro Network Accessibility Measure and Evolution Analysis: A Case Study of the City of Guangzhou, China

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Abstract: Urban rapid rail transit networks are important infrastructures of modern urban transportation systems in the large cities with huge population. Their accessibility has a large impact on urban spatial patterns, residents' travel behaviors and the quality of urban living environment. Therefore, this study aims to evaluate the accessibility of an urban rapid transit network in the city of Guangzhou, China. This study considers time and transfer constraints as measures to assess connectivity between nodes in the network. These measures generate indices of the network accessibility, where matrices of the costs of route changes and travel times between nodes are derived. Based on the matrices, transfer-based and time-based accessibility coefficients at any node in the network are computed and thus isochrones are derived to illustrate the evolution of the accessibility spatial patterns. The results revealed that the Guangzhou metro network development has a valuable impact on urban accessibility and that the importance of the influence of transfer stations. It is also appeared that the metro network development has been though as one of the effective measures to tackle the urban transportation issues.

Key words: Accessibility, metro network, transfer, travel time

INTRODUCTION

"Accessibility", reveals the qualities of travel opportunities between different regions through a transportation network, has been widely applied to evaluate the structure and connectivity of a transportation network and then to investigate and assess available transportation environment in a given region (Hagerstraand, 1970; Miller and Wu, 2000).

Much of the literature on transportation studies has provided many methods for the accessibility measures in different domains, such as expressways networks (Li and Shum, 2001), rails networks (Wang *et al.*, 2009), air lanes networks (Bowen, 2000) and regional transportation networks (Jin *et al.*, 2009; Mavoa *et al.*, 2012; Jiang *et al.*, 2012). The methods applied vary but share the objective of quantitatively studying the distribution in space of transportation environment based on travel-time (Deng *et al.*, 2012) and distances (Wang *et al.*, 2009). These methods reveal travel constraints closely related to distance (Wang, 2005), travel time (Bruinsma and Rietveld, 1993; Gutierrez and Urbano, 1996) and other aggregated transportation costs (Linneker and Spence, 1992; Spence and Linneker, 1994).

From the perspective of urban planning and economic development, several studies explored the interactions between transportation accessibility and urban planning (Sohn, 2006; Wang *et al.*, 2009; Xiang and Chen, 2010; Gutierrez, 2001). Moreover, a public transportation system should also provide efficient services to the general public. In particular, the accessibility of an urban rapid rail transit network should help to evaluate the passengers' needs that the network has to meet. In a previous work a multi-modal approach has been introduced for the modeling and representation of the transportation networks in the city of Guangzhou, China (Chen *et al.*, 2011). The objective of this study is to extent this work by an evaluation of the spatial characteristics of a metro network accessibility regarding public transportation passengers' travel demand. This approach is applied to the city of Guangzhou in China, whereas the public transportation passengers' prime concerns are the number of route transfers and travel times (Yang *et al.*, 2000).

Transfer and travel time are quantitative indices that assess connectivity between nodes in the metro network. Furthermore, in order to measure the overall network accessibility, matrices of the number of route transfers

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and shortest travel time between any two nodes in the network are constructed. Based on the matrices, transfer-based and time-based accessibility coefficients at any node are computed and thus isochrone maps are applied to illustrate and analyze the evolution of the network accessibility in Guangzhou.

METHODOLOGY

Overall network connectivity indices: One of the nice properties of an urban network is that its structural properties can be analyzed using graph-based measures. Several approaches have been suggested to quantify network connectivity (Liansheng, 1998; Black, 2003; Wang *et al*., 2009), including beta index (β), cyclomatic number (μ), alpha index (α) and gamma index (γ). Amongst these indices, the Beta index (β), gives the average number of edges (e) per node (n) in a given network:

$$\beta = \frac{e}{n} \tag{1}$$

The Cyclomatic number (μ) gives the number of circuits to indicate gap between e and n while counting for the number of sub networks q (q = 1 for a fully-connected network), as follows:

$$\mu = e-n+q \tag{2}$$

The alpha index (α) is defined as the proportion between the actual and maximal number of circuits in a fully-connecting planar network, it is given as:

$$\alpha = \frac{e-n+q}{2n-5q} \tag{3}$$

The gamma index (γ) is the ratio between the actual and maximal number of edges:

$$\gamma = \frac{2e}{n(n-1)} \tag{4}$$

An immediate property of these indices is that the higher their values the higher the overall connectivity of the networks.

Matrix and nodal accessibility coefficients: The indices of overall network connectivity are essentially structural but cannot reveal the functionality of a given network as it should be denoted by indices that can assess the performance of the urban network regarding the way people displacements can be performed.

Therefore, a transfer matrix R and a time matrix T are introduced and thus described, respectively as:

$$R = [r_{ij}]_{n\times n} \tag{5}$$

$$T = [t_{ij}]_{n\times n} \tag{6}$$

In a transfer matrix R, each element r_{ij} (i.e., the ith row and jth column) denotes the number of route transfers between an origin i to a destination j. If $r_{ij} = 0$, with $i \neq j$, then there is a direct route between the nodes i and j. Also, the number of route transfers from node i to all other nodes is the sum of the ith row and then given as:

$$R_i = \sum_{j=1}^{n} r_{ij} \tag{7}$$

where, R_i is the sum of the minimum number of route transfers from the node i to all the other nodes of the network. Small R_i values for a given node i denote a relatively well connected node in the network. The number of route transfers for all possible routes of the overall network can be calculated by the sum of all row sums.

This overall measure of transfer can be projected at the local level to evaluate the performance of a given node in a network. That nodal transfer-based accessibility coefficient at a given node i, i.e., the ratio of R_i at node i to the network average across all nodes (j = 1, 2,..., n) is given by:

$$A_{ri} = R_i \Big/ \left(\sum_{j=1}^{n} R_j / n \right) \tag{8}$$

If $A_{ri}>1$, the transfer accessibility coefficient at node i is below the network average. Small A_{ri} correspond to good transfer accessibility at node i. As the case study will reveal, the index A_{ri} tends to favor nodes near the center of the network.

Similarly, a time matrix T is introduced in this study, where each element t_{ij} (in the ith row and jth column) denotes the actual travel time between an origin i and a destination j. In all other cases, the actual travel time (t_{ij}) between nodes i and the nodes j that can be reached is computed by the shortest time path between those two nodes in the network.

In the matrix T, if $t_{ij}=0$, i=j. For a full-connected network (e.g., a metro network), t_{ij} is given as finite as there is a direct or by transfer route between any i and j. As for the definition of t_{ij}, the minimum amount of travel time from node i to all other nodes is the sum of the i^{th} row in the matrix T and is given as:

$$T_i = \sum_{j=1}^{n} t_{ij} \tag{9}$$

Moreover, the minimum travel time regarding all possible origin-destination transfers in the network is given by the sum of the ith row of the matrix T. Therefore, the nodal time-based accessibility coefficient at a given node i is given by the ratio of the sum of the ith row on that node i to the network average across all nodes (j = 1, 2,…, n), as follows:

$$A_{ti} = T_i / \left(\sum_{j=1}^{n} T_j / n \right) \tag{10}$$

If $A_{ti}>1$, the nodal time-based accessibility coefficient at that node i is below the network average (conversely, the coefficient ($A_{ti}<1$) is above network average). Small A_{ti} reflect good time-based accessibilities. As for transfer indices, the index A_{ti} tends to favor nodes near the center of the network.

STUDY AREA

The Guangzhou administrative area comprises ten urban districts and two suburban counties. Amongst the districts, Liwan, Haizhu and Yuexiu are the historically downtown centers of the city. Tianhe is the new downtown centre and has attracted a lot of mobility and commerce activities. The historical and new downtown centers form the "core" of the city (Fig. 1).

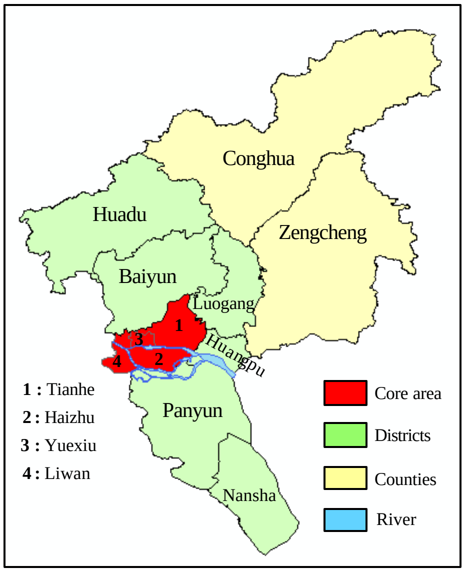

Fig. 1: Administrative area and the “core” of the city of Guangzhou

The Guangzhou metro network has been progressively constructed since 1993. Nowadays, the metro network has 8 lines with a total length of 232 kilometers and 203 stations. Its development may be taken apart into three stages, i.e., preliminary construction (before 2002), networking (2003-2009) and network intensification (after 2009).

Before 2002, another metro line call as Line 2 was constructed and opened. Line 1 and Line 2 went through the “core” area of city and shape a “+” frame with the transfer station, i.e., “Gongyuan Qian”.

During 2003-2009, the metro network development stepped into a networking stage. Three new metro lines were constructed in operation, i.e., line 3-5. The new lines and line 1-2 constituted the skeleton of the metro network.

After 2009, the network development focused on intensification and optimization. In this stage, the branch of Line 3 from Linhe Xi to Airport South was in operation. Meanwhile, the intercity metro line to connect the cities of Guangzhou and Foshan was constructed and opened. Moreover, an underground Automated People Mover (APM) system was established to serve the central business district of Zhujiang New Town (the center of Tianhe District) and is connected to line 3 at the transfer stations of Linhe Xi and Chigang Pagoda, respectively.

Importantly, two segments, one running from Changgang to Guangzhou South Railway Station and the other running from Changgan to Fenghuang Xincun, were constructed in 2010. For improving the service efficiency and transportation capacity, the segments and stations of line 2 were reorganized. The previous line 2 was taken apart into two parts at the station of Xiaogan. One part (Sanyuan Li-Jiannan Xi) connected the segment running from Changgan to Guangzhou South Railway Station to organize the new line 2. The other part (Xiaogang-Wansheng Wei) connected to the segment running from Changgan to Fenghuang Xincun for composing Line 8. The transfer station of line 2 and 8 is the station of Changgan. The metro network spatial distribution in this stage illustrates that the network extended around the core area of city (Fig. 2).

With the spatial expansion of the metro network, the travel modal splits in Guangzhou have revealed significant changes over the past decade. Table 1 shows a sharp increase of the number of trips using metro mode during 1999-2010. Also, Table 1 presents a fact that the bus mode still plays a significant role in the public transportation system in the city of Guangzhou in 2010, although its ratio in modal shift has been declining since 2005. However, the ratio of the trips using ferry mode in modal split had been gradually falling from 2.1-0.3%

Table 1: Modal shift of different trips in Guangzhou during 2002-2010

Year	Bus (%)	Metro (%)	Taxi (%)	Ferry (%)
2010	56.1	26.7	16.9	0.3
2009	63.3	17.6	18.7	0.4
2005	69.6	8.0	21.6	0.6
2002	79.6	2.8	16.5	1.1
1999	77.4	1.9	18.6	2.1

Fig. 2: Spatial distribution of the metro network in the core area of Guangzhou in 2010

during 1999-2010. This implies the development of metro mode had a large influence on the citizens' travel behavior in Guangzhou.

RESULTS AND ANALYSIS

Evaluation of network expansion: The metro network spatial extension impact the topological properties of the network and this should be reflected by the overall network spatial connectivity. Table 2 shows the evaluation of the overall metro network connectivity in different stages by using the beta index (β), cyclomatic number (μ), alpha index (α) and gamma index (γ) which have been previously introduced. The table indicates that the Guangzhou metro network appeared a tree network structure and its connectivity quality was lower before 2005, as the value of β was less than 1 and $\mu = 0$. Till 2005, with the opening of the branch of line 3, the network appears as a cyclomatic network due to $\beta = 1$ and $\mu = 1$. In 2010, the number of circuits (i.e., μ) reached the value of 6. This implies that the network spatial structure has been relatively optimized and its connectivity quality was improving accompanied by the expansion of the metro network during 1999-2010. Also, Table 2 reveals that the values of α and γ were relatively lower during the network development from 1999-2010. This reflects a fact that the overall metro network connectivity is still at a relative lower level.

Table 2: Shift of the overall metro network connectivity indices by Guangzhou (1999-2010)

	Year				
Index	1999	2002	2005	2009	2010
β	0.94	0.94	1.00	1.04	1.04
μ	0.00	0.00	1.00	4.00	6.00
α	0.00	0.00	0.01	0.03	0.02
γ	0.36	0.34	0.34	0.55	0.35

Time-based accessibility evolution: The evaluation of the overall network growth reveals several trends regarding the evolution of the network spatial connectivity. Furthermore, the transfer matrix R and travel time matrix T are implemented to complement the overall network connectivity indices for reflecting the network accessibility. To build the matrix R and T, the transfer- and time-based accessibility coefficients at each metro station, i.e., A_{ri} and A_{ti} are calculated, respectively.

Regarding the values of A_{ti} at any station in the metro network, the isolines maps are generated by Inverse Distance Weighted interpolation (as implemented in ESRI ArcGIS). These maps illustrate the spatial pattern of the network time-based accessibility in 2002, 2005, 2009 and 2010 (Fig. 3a-d), respectively. The results that emerge can be commented as follows: (1) The number of stations with good time-based accessibility (A_{ti}<1) in the network gradually extended from 2002 to 2010 but their locations are still in the core area of the city, (2) As only one line, i.e., line 5 was in operation in 2009 and the stations are intensively distributed in the East and the core area of the city, travel times through the network are increasing as it is extending (Fig. 3c). This causes a decrease of the accessibility of the South area. With the intensification of the network in 2010, travel times through the network are shortened again (Fig. 3d) and (3) The spatial patterns of time-based accessibility gradually evolved into a concentric circle spatial structure with the center of Yuexiu District from 2002-2010. This implies that the time-based accessibility in the center of Yuexiu District has the highest level (A_{ti}<0.8) and radiates out from the center.

Transfer-based accessibility evolution: Based on the nodal transfer accessibility index (i.e., A_{ri}) of each station (node), Figure 4a-c illustrates the spatial distribution of the stations represented by the values of A_{ri} in 2005, 2009 and 2010, respectively. Indeed, transfer stations have

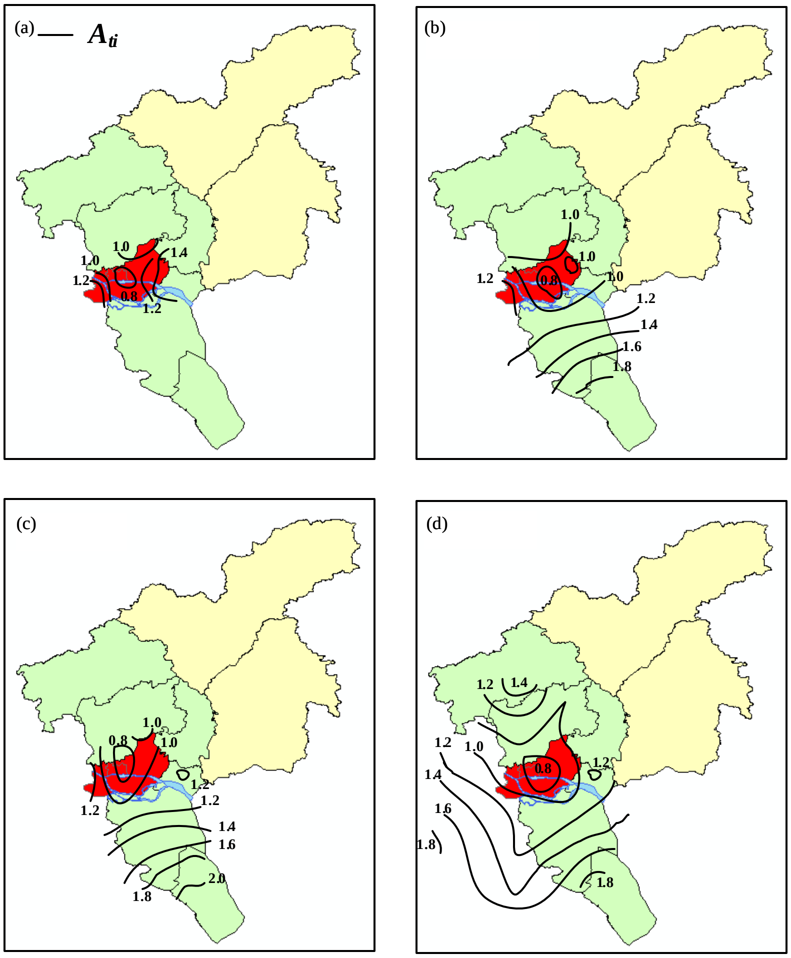

Fig. 3(a-d): Isoline maps of the evolution of network time-based accessibility spatial patterns in (a) 2002, (b) 2005, (c) 2009 and (d) 2010

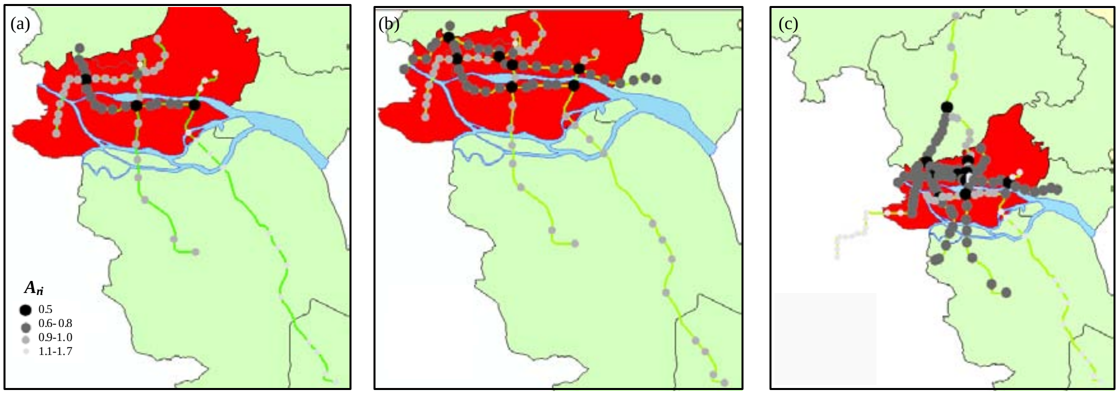

Fig. 4(a-c): Spatial distribution of the stations represented by the values of A_{ri} in (a) 2005, (b) 2009 and (c) 2010

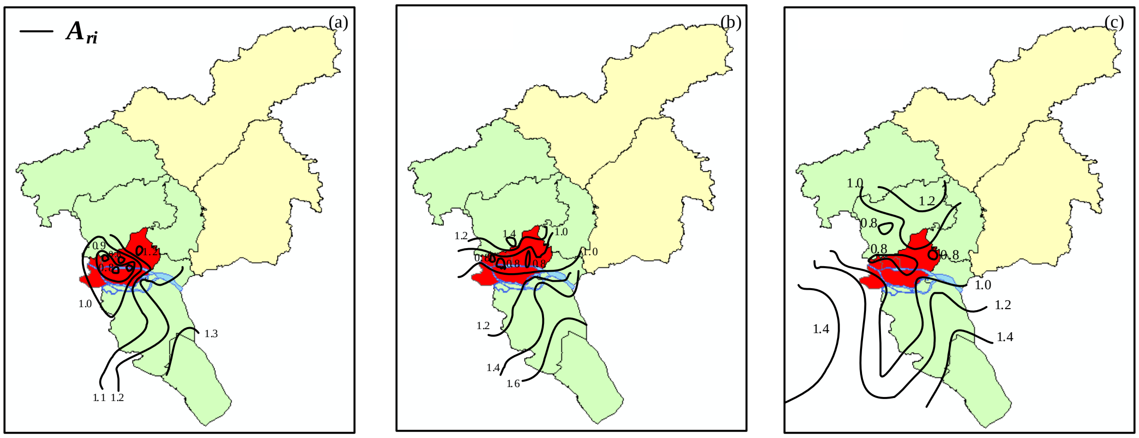

Fig. 5(a-c): Isoline maps of the evolution of network transfer-based accessibility spatial patterns in (a) 2005, (b) 2009 and (c) 2010

lower A_{ri} values than other stations. Moreover, the metro line with large number of transfer stations implies that its overall transfer accessibility is relatively higher. Figure 5a-c shows the transfer-based accessibility spatial evolution through the isoline maps according to the A_{ri} values of stations. Overall the following observations can be made: (1) Transfer stations have significant impacts on the improvement of the urban accessibility, (2) Stations which have high quality transfer-based accessibilities are intensively distributed in the core area of the city. Moreover, the stations of line 1 and 5 indicate the better accessibilities, as these two lines have more transfer stations. This confirms that the best transfer accessibility is intensively distributed in the core area of the city, as shown in the spatial distribution of the accessibility in 2010 (Fig. 5c) and (3) Transfer-based accessibility spatial patterns present a complicated circle structure with multiple centers. This stresses the factor that transfer station is significant for the improvement of the urban accessibility. As a result, the metro network planning not only considers the connectivity between stations in space and time but also the location of transfer station to improve the transfer environment between metro lines.

All the findings outlined above reveal the spatiotemporal characteristics of the metro network accessibility and reflect the demand of the optimization of the public transportation network structure in the city of Guangzhou. This stresses the crucial importance of the integration of an evaluation of network accessibility and a multi-modal network modeling and representation approach which has been introduced in the previous study (Chen *et al*., 2011).

CONCLUSION

The experimental research presented in this study applies several transportation indices, including number of route transfers and travel times to analyze the metro network accessibility and spatial evolution in Guangzhou. The findings of the accessibility evaluation approach and the trends revealed by the application to the urban network of Guangzhou outline the following aspects: (1) Time-based accessibility generates a concentric spatial structure. Accessibility quality gradually decays from the center outward. With the influence of the locations of transfer stations, the decrease of accessibility shows different trends. For example while Line 5 is used as the dividing line of the North-South area of the city, it can be recognized that the accessibility in the North area is superior to the one of the South area due to more transfer stations located in the North area and (2) Regarding transfer-based accessibility, transfer stations have crucial effects on urban accessibility. However, the unbalanced spatial distribution of transfer stations shows that accessibility in the outskirts of the city cannot be improved with the expansion of the transportation network. To deal with this issue, the annular lines to connect the stations located in the outskirts provide visual spatial measures. Such annular lines reveal an increase the number of the transfer stations in the outskirts of the city and thus promotes the accessibility in these areas.

Overall this approach has been successfully implemented thanks to the relative efficiency of the graph-based model that reflects the main functional and structural properties of the urban transportation network. Therefore, the potential of the modeling framework by integrating origin-destination surveys should been extended to confront the findings of the approach with transportation behaviors in Guangzhou, China.

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