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A spatio-temporal modelling approach for the study of the connectivity and accessibility of the Guangzhou metropolitan network

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ABSTRACT

The urban growth of large cities in China is at a critical stage with the booming of the economy and impressive increase of the population and traffic demand. This paper studies and qualifies the growth and accessibility of a rapid rail transit network, and characterizes the relations with urban development using a spatio-temporal modelling approach. Several measures of the network topological structure, i.e., *beta index* (β), *cyclomatic number* (μ), *alpha index* (α) *and gamma index* (γ), are selected in order to examine and quantify the overall metro network growth of the city of Guangzhou in China. The results show that the current spatial connectivity of the Guangzhou's metro network is relatively low, this stressing the need to augment the reliability of the connections between the network nodes, and to increase the number of circuits in the network. A travel-time matrix is modelled and evaluates the nodes accessibility and characterizes the spatio-temporal evolution of the metro network. The spatial interaction between the different nodes of the network, as well as nodes accessibility are analyzed and derived from a potential-based model. The extension of the metro network clearly shows a dramatic tendency of positive accessibility evolution but with regional differences. In particular, the core of the city is surrounded by areas with highest accessibility values and gradually expanding outward from the core, while the locations of transfer stations have significant influence on the variation of network time-based accessibility. Taking into account different network development scenarios, the approach reveals regional accessibility differences in the metropolitan area of the city of Guangzhou, this clearly illustrating the impact of network accessibility in urban development.

1. Introduction

Accessibility is generally described as "the ease and convenience of access to spatially distributed opportunities with a choice of travel" (USDE, 1996). Accessibility has been an essential measure for assessing a network's spatial connectivity and evaluating travel opportunities in transportation network planning (Morris et al., 1979; Pirie, 1981). Accessibility is a multi-dimensional concept that integrates various network measures such as network connectivity and node accessibility (Garrison and Marble, 1974). Several methods have been introduced to reveal the connectivity and nodal accessibility of a given transportation network. Hansen (1959) identified accessibility as "the potential of opportunities for interaction," and provide a potential-based model to evaluate accessibility in metropolitan areas. Garrison (1960) introduced several graph theoretic concepts to analyze the topological accessibility of a transportation network using accessibility indices, that is, overall network connectivity measures (i.e., *beta index*, *association number*, *alpha index*, *gamma index*) and node accessibility indices (i.e., *Shimbel index* and *nodal degree*). Transportation research has long applied these network accessibility measures based on graph theory concepts (e.g., Rühl, 1991; Blum et al., 1992; Linneker and Spence, 1992; Bowen, 2000; Li and Shum, 2001; Zhang and Lu, 2006; Jeong et al., 2007; Bharill and Rangaraj, 2008; Kreutzberger, 2008; Wang et al., 2009; Jin et al., 2009; Mavoa et al., 2012; Deng et al., 2012). The graph-based analysis applied vary, but share the objective of quantitatively studying the spatial distribution of travel opportunities based on travel time (e.g., Lutter et al., 1992; Bruinsma and Rietveld, 1993; Gutiérrez and Urbano, 1996; Deng et al., 2012), distance (e.g., Keeble et al., 1988; Spence and Linneker, 1994; Jin et al., 2009), potential accessibility model (e.g., Hansen, 1959; Geertman et al., 1995), or even structural-based approaches such as illustrated by spatial syntax studies (e.g., Cheng et al., 2007) to mention a few examples. Similar studies have been also applied to qualify the connectivity of railway networks, and to

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assess available travel opportunities in a given station's transportation environment at national and regional scales since early 1990s (e.g., Rühl, 1991; Blum et al., 1992; Murayama, 1994; Bharill and Rangaraj, 2008; Jeong et al., 2007; Kreutzberger, 2008; Wang et al., 2009; Marína and García-Ródenas, 2009; Ahlfeldta and Wendlandb, 2011; Deng et al., 2012).

Indeed, urban transportation networks such as urban rapid transit systems have essential impacts on travel opportunities, and land use change, this having a strong influence on urban spatial structures as well as socio-economic activities (Meyer and Miller, 2001). Advances in accessibility have improved spatial connectivity within urban areas and stimulated urban growth (Johnson, 1967; Jackson, 1985; Bhatta, 2010). Conversely, urban transportation accessibility is significantly influenced by, and acts on urban growth over time (Siming and Yiman, 2001). A variety of factors trigger urban transportation network development and drive changes on the accessibility they provide, including urban growth, land use change and population agglomeration, this being particularly the case for highly-densely developed cities, such as the city of Guangzhou in China. Urban development significantly increases urban mobility demand and transportation opportunities, but also brings novel traffic issues and transportation development pressure (Brueckner, 2000; Cervero, 2003; Allen and Lu, 2003; Millot, 2004; Zhou and Yan, 2005; Bhatta, 2010). Many urban planning studies have studied the causes and effects of transportation development and urban growth (e.g., Brotchie, 1991; Parker, 1995; Priemus et al., 2001; Gutiérrez, 2001; Sohn, 2006; Fan et al., 2009; Xiang and Chen, 2010; Jiang et al., 2012; Deng et al., 2012). In particular, several researches have investigated the mutual relationships between transportation system development and urban growth in the city of Guangzhou, thus demonstrating that the transportation system plays a crucial role in the evolution of the urban spatial structure. For instance, Yan and Mao (2004) discussed the relationship between, and respective evolution of the urban transport system and land use in the city of Guangzhou. Mao and Yan (2005) studied the impacts of the urban transport system on the spatial patterns, and conversely, that emerge in the city of Guangzhou. Lin and Lu (2011) showed that major transportation facilities projects implemented since 1949 have brought significant changes in the Guangzhou's urban spatial structure and urban form. However, there is still a lack of studies on the assessment of the transportation network growth and the implications of network connectivity and node accessibility, and their impact on urban development. In order to compare the evolution of the Guangzhou metro network accessibility and connectivity with the expansion of the city, there is still a need to develop a spatio-temporal modelling approach that will measure and qualify these indices and patterns.

In a previous work we introduced a multi-modal approach for the representation of the transportation system of the city of Guangzhou (Chen et al., 2009, 2011). The objective of the present paper is to extent our previous work by a spatio-temporal modelling approach that qualifies the accessibility and connectivity properties of the metro network over time, and the close relationship with urban development. Several graph-based indices and matrix analysis are applied to reveal the emerging structure and accessibility patterns of the Guangzhou metro. Several potential-based scenarios are integrated to evaluate the interactions between the different nodes of the network, this showing different attractiveness properties. Several maps derived from node accessibility measures show and illustrate the different spatio-temporal patterns and evolution of the metro network accessibility. This helps to explore the overall network connectivity and nodal accessibility transformation over time, as well as implications on regional development, and accessibility differences in the metropolitan area of the city of Guangzhou.

2. Modelling approach

Network connectivity and available travel opportunities are basic measures of "accessibility". Over the past years, several methods based on graph theory accessibility models have been developed in the field of transportation research. Several graph theoretic indices evaluate the topological accessibility of a given urban network and node accessibility (similar indices has been proposed to evaluate the structural properties of a given urban network by space syntax studies (e.g. Cheng et al., 2007)). Several indices have been suggested to quantify the overall network connectivity, including *beta index* (β), *cyclomatic number* (μ), *alpha index* (α) *and gamma index* (γ) (e.g., Cheng, 1998; Black, 2003; Wang et al., 2009), they are defined as follows:

- The *Beta index* (β) gives the average number of edges (e) per node (n) in a given network (Wang et al., 2009), i.e., $\beta = e/n$ $(0 \leqq \beta \leqq (n-1)/2)$.
- The *Cyclomatic number* (*Associated Number*) gives the number of circuits to indicate a sort of gap between e and n while counting for the number of sub networks q ($q = 1$ for a fully-connected network), i.e., $\mu = e - n + q$ $(0 \leqq \mu \leqq (n-1)(n-2)/2)$.
- 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: $\alpha = 2\mu/(n-1)(n-2) = (e-n+q)/(2n-5q)$ $(0 \leqq \alpha \leqq 1)$.
- The *Gamma index* (γ) is the ratio between the actual and maximal number of edges: $\gamma = 2e/n(n-1) = e/[3 \times (n-2)]$ $(0 \leqq \gamma \leqq 1)$.

An immediate property of these indices is that the higher their values, the higher the overall connectivity of the network. However, those indices are essentially structural and cannot reveal the functionality of a given network as it should be denoted by indices that will rather evaluate the performance of the nodes' available travel opportunities regarding the way people displacements can be performed.

In order to assess the nodal accessibility of a metro network, each metro station is abstracted to represent a node of the network. Among the indices used for the measure of nodal accessibility, *Shimbel index* (or *Shimbel distance*) has been widely examined to qualify available travel opportunities of a given node, which is a measure of a node's accessibility representing the sum of the length of all shortest paths connecting all other nodes in the graph (Black, 2003). *Shimbel index* can be calculated based on a distance matrix which is given by:

$$D = [d_{ij}]_{n \times n} \tag{1}$$

where d_{ij} indicates the distance of shortest path between node i and j. Therefore, *Shimbel distance* is the sum of the ith row in matrix $\boldsymbol{D}$, i.e., the minimum amount of distances of all shortest paths from node i to all other nodes:

$$D_i = \sum_{j=1}^{n} d_{ij} \tag{2}$$

Nevertheless, a shortest path (composed of a set of consecutive links involving different nodes) may not be the best choice for passengers, if they are required to take time to change routes. The yearbook of Guangzhou transportation development in 2012 reported more than 80% of passengers were most concerned with the time cost in a trip using metro mode (GITP, 2012). We then consider travel time as the constraint to assess nodal accessibility. To achieve this target, a time matrix $\boldsymbol{T}$ is built:

$$T = [t_{ij}]_{n \times n} \tag{3}$$