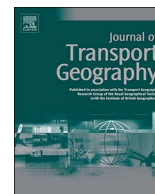




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Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Determining intra-urban spatial accessibility disparities in multimodal public transport networks

Jie Chen^{a,b}, Jianhua Ni^a, Changbai Xi^a, Siqian Li^a, Jiechen Wang^{a,c,d,*}^a Department of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, Jiangsu Province 210023, PR China^b Department of Surveying and Mapping Engineering, Datong University, Datong, Shanxi Province 037009, PR China^c Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, Nanjing, Jiangsu Province 210023, PR China^d Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing University, Nanjing, Jiangsu Province 210023, PR China

ARTICLE INFO

Keywords:

Accessibility
Multimodal modeling
Public transport
Open data
Multilevel grid

ABSTRACT

Urban rail systems have been added to public transport systems, thereby changing distribution disparities in urban spatial accessibility. These disparities reflect both the ability of the public transport system to meet the needs of residents and the locational pros and cons of public service facilities. In this paper, integrated accessibility metrics are used to assess the disparities in Nanjing, Jiangsu Province, China. This is achieved by dividing the urban space into a multilevel grid that can be easily combined with grid-based population data to facilitate accessibility modeling, calculation, and evaluation. Additionally, an acquisition method for more accurate travel time data in the multimodal public transportation network was developed on the basis of an Internet mapping service. This provides a realistic, multimodal, door-to-door modeling approach that avoids the requirement of building complex traffic networks through Geographic Information System (GIS) software and simplifies road network modeling efforts. The results show that this modeling method can be used to reflect the accessibility disparities in the Nanjing urban space objectively and accurately.

1. Introduction

Faced with increasing urban populations, traffic congestion, and environmental impacts, public transport (metro or bus) has attracted more attention from traffic and urban planners than private motorized vehicles (Benenson et al., 2011; Hess, 2005; Kawabata and Shen, 2006; Shen, 1998a, 1998b; Martin et al., 2008). In addition, public transport is more conducive to healthy physical activity owing to walking to the initial bus stops or metro stations, transferring, and walking to the final destination (Elias and Shiftan, 2012; Pratt et al., 2012; Peipins et al., 2011; Badland et al., 2013). In particular, given its large transportation volume, speed, and punctuality, public transportation can be a more convenient way for people to travel. However, given the construction cost of transport facilities, metro stations are usually constructed in places where the population is more concentrated or socio-economic activities are more frequent. The benefits brought by bus/metro stops/stations are thus spatially unbalanced in the city and are usually limited to transport facilities around and along a certain transportation corridor. With changing land use and economic growth, this corridor may eventually develop into the core of a region. On the contrary, areas with no metro stations, which are far away from public transport facilities or

are at the periphery of a region, will be in an adverse transportation location; their development potential is subject to great restrictions. In order to ensure fair access to transport services and to reduce the differences in and interregional generation gaps of accessibility distributions (Kwok and Yeh, 2004; Langford et al., 2012; Wang and Chen, 2015; Cheng and Bertolini, 2013), it is necessary to analyze and measure the spatial distribution of current urban space accessibility. The results of this analysis can help to allocate public transport service facilities reasonably and improve the efficiency of these facilities.

At present, accessibility measurement models and methods are categorized into four types: infrastructure-based accessibility measures, location-based accessibility measures, person-based measures, and utility-based measures (Geurs and van Wee, 2004; Handy and Niemeier, 1997; Lei and Church, 2010; Liu and Zhu, 2004; Kwan, 1998). However, all of these models and methods have certain defects. (1) In the process of evaluating, measuring, and modeling accessibility, it is often necessary to rely on simplifying the space, abstracting the irregular administrative regions (or street districts) as point sets, ignoring the dynamics of people's daily lives, and disregarding the terrain and population density. (2) The calculation of time is mostly realized using the network analysis (O-D) matrix tool in the ArcGIS software package, in

* Corresponding author at: Nanjing University, Nanjing 210023, China.

E-mail addresses: chenjie_301@126.com (J. Chen), neejianhua@126.com (J. Ni), xicb11@126.com (C. Xi), lisiqian_1994@163.com (S. Li), wangjiechen@nju.edu.cn (J. Wang).

which different levels of traffic lines are set to their appropriate speeds and then divided by the distance of the traffic line (Liu and Zhu, 2004; O’Sullivan et al., 2000). The times of the different components of a multimodal trip (walk time, wait time, transfer time, congestion time, and in-vehicle time) were rarely taken into account. (3) The scale of accessibility research is not uniform. Most research has been carried out on a national or intercontinental scale, focusing on potential spatial accessibility patterns to compare future trends and metrics (Gutiérrez and Urbano, 1996; Gutiérrez, 2001; Holl, 2007), with less work focused on the microscopic scale such as urban areas. Given that a large fraction of the population and industry are gathered in cities, that urban road networks are complex, and that people can select from diverse traffic modes in urban areas, it is difficult to determine a more reasonable travel time.

Therefore, we need to provide a method to measure public transportation accessibility to solve a multimodal network problem with time as a constraint (Benenson et al., 2011; Lei and Church, 2010; Martin et al., 2008; Mavoa et al., 2012; Salonen and Toivonen, 2013; Tribby and Zandbergen, 2012; Liu and Zhu, 2004; O’Sullivan et al., 2000; Peipins et al., 2011). Most of these papers propose simplifying different travel time components, thus creating a multimodal public transport network model integrated into standard GIS software. However, the wait time at the initial stop/station or that involved in a transfer is simplified as half of the headway time (the time interval between vehicle departures) (Gent and Symonds, 2004; O’Sullivan et al., 2000; Tribby and Zandbergen, 2012; Peipins et al., 2011). In-vehicle travel time is represented as an average traveling speed that is calculated from the time spent on the entire route divided by the entire route length (Liu and Zhu, 2004; O’Sullivan et al., 2000).

The accuracy of this travel time calculation is an improvement compared to what was done in the past. However, the travel time is still underestimated or overestimated in many respects. For example, the difference in bus speeds between suburban areas and in the city center, the abilities of travelers to optimize their journeys, and the different pedestrian walking speeds used in different studies (Tribby and Zandbergen, 2012; Peipins et al., 2011; Mavoa et al., 2012) all contribute to inaccuracies. Additionally, the waiting time (Mavoa et al., 2012; Peipins et al., 2011) and transfer time between different modes of transport are often overlooked (Liu and Zhu, 2004) or treated as being uniform (Mavoa et al., 2012; O’Sullivan et al., 2000).

To address the limitations of the standard Geographic Information System (GIS) network model, which leads to simplifications of the different travel time components, we propose a realistic multimodal network door-to-door approach based on an Internet mapping service that integrates public transport and metro schedules.

The remainder of this paper is organized as follows. Section 2 describes the methodology. Section 3 provides an overview of the study area and the implementation of a multilevel grid division method of the study area. Section 4 presents and discusses the results, and Section 5 provides conclusions and an outlook for the future.

2. Methodology

2.1. Indicators of measuring accessibility

There are two essential elements for accessibility measurement (Dalvi and Martin, 1976). The first element is the travel time, making use of the available transport models from an origin i_n (individual) to a destination j_m (attraction). The second element is the potential of a different destination j_m (attraction) to the origin i_n (individual), which reveals the size of the attraction from i to j for a trip based on a given purpose, as shown in Fig. 1.

Thus, two general accessibility metrics are derived from these two elements: the potential accessibility (PA) and weighted average travel time (WATT). The PA combines the time from the origin i (individual) to the destination j (attraction) with the utility of different destinations j

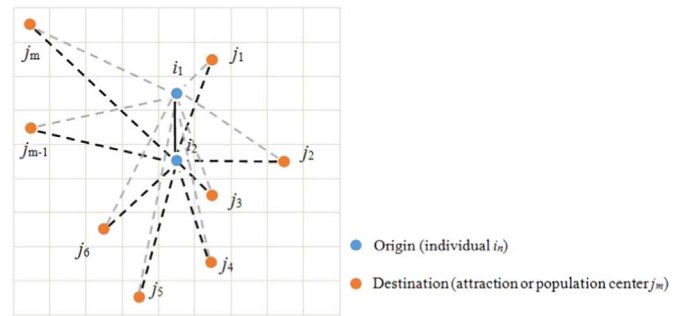


Fig. 1. Relationship between an origin (individual i_n) and a destination (attraction or population center j_m).

(attraction) into a single indicator, allowing direct comparison of the accessibility of different locations (individual i). The WATT is a modified potential model that uses the travel probability to assess the attractiveness of each destination point j to the origin i . These two indicators can be used to measure the accessibility of any location in an urban area from the perspective of competitiveness or attractiveness and travel time.

The concept of a potential model is related to that of a gravity model in terms of the spatial interaction. A gravity model was first noted and is based on an analogy between the interaction of groups of people and the attraction of physical masses (Stewart, 1941). Rich argues that locations near large masses have a large potential and are often regarded as the most central, most attractive, or most accessible to the gathering population (Rich, 1980; Geertman and Van Eck, 1995).

The classical potential accessibility equation is expressed as

$$P_i = \sum_j \frac{M_j}{t_{ij}^\alpha} \quad (1)$$

where P_i is the PA at location i (origin), M_j is the size of location j (attraction), and t_{ij} is the time/distance between i and j . In this equation, α is a parameter, usually between 1 and 2, that reflects the rate of increase in the friction of the time/distance.

The average travel time from location i to all of the locations j connected to i can be expressed as (Geertman and Van Eck, 1995)

$$T_i = \sum_j (p_{ij} \times t_{ij}) \quad j = 1, 2, \dots, k \quad (2)$$

where p_{ij} is the proportion of the population living at location i that travels to location j , t_{ij} is the shortest-path travel time through the network between locations i and j , and k is the total number of destinations from location i .

On the basis of the gravity-like interaction pattern assumption (Geertman and Van Eck, 1995), the population traveling from location i to location j is directly proportional to the mass of that destination M_j and inversely proportional to a certain power of the travel time t_{ij} between i and j . Therefore, the value of p_{ij} is calculated with

$$p_{ij} = \frac{M_j/t_{ij}^\alpha}{\sum_k (M_k/t_{ik}^\alpha)} \quad (3)$$

Combining Eqs. (1) and (2) yields

$$T_i = \frac{\sum_j (M_j/t_{ij}^{\alpha-1})}{\sum_k (M_k/t_{ik}^\alpha)} \quad (4)$$

When $\alpha = 0$, Eq. (3) becomes

$$T_i = \frac{\sum_j (M_j \cdot t_{ij})}{\sum_j M_j} \quad (5)$$

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