



Two Dimensions for Determining and Analyzing the Patterns of the Modal Accessibility Gap in Nanjing, China

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Abstract

Measuring the modal accessibility gap (MAG) is useful for evaluating sustainable transportation development and urban land use. Meanwhile, reducing reliance on private transport (e.g., car use) and raising public transport usage (e.g., bus, metro, light rail, bicycle) is frequently a major goal of transport strategies. Against this background, this study measures the MAG in multi-modal transportation networks from two perspectives: mobility (travel modes and traffic conditions) and proximity (the location and attractiveness of the destination) and describes the methodology developed for an application across the metropolitan area of Nanjing, China. The results show substantial differences between public and private transport in a multi-modal urban network environment based on a realistic “door-to-door” model. In addition, we find that the accessibility advantage of cars is always better than the transit and cycling modes but only from a mobility perspective. The analysis of the sustainability of urban transport should also take account of the location and service capability of the destination and the influence of traffic congestion. The patterns of the smallest MAG scores between the transit and car modes are concentrated along metro and bus routes, and thus they change with traffic fluctuations. On the contrary, the patterns of the smallest MAG scores between the cycling and car modes are concentrated in central urban areas and are thereby affected by traffic conditions including road destiny, river obstacles, and the cross-river channel. Finally, the range of the lowest MAG scores shows a broader distribution in central urban areas in peak hours compared with in off-peak hours.

Keywords Modal accessibility gap · Mobility · Proximity · Multi-modal transport network

Introduction

With improving socioeconomic standards, the number of vehicles in China has risen sharply, and mobility has therefore been increasing. As a result, urban traffic

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problems have become increasingly prominent. Traffic congestion in and around the commercial centers, hospitals, and schools of large cities is particularly severe (Banister 2011; Reggiani et al. 2014) and this trend is threatening urban surroundings (Jones and Lucas 2012; Saghapour et al. 2016). Hence, sustainable transportation has become a transport objective worldwide (Banister 2000, 2008; Chakraborty 2017; Albacete et al. 2015).

To improve sustainable transport development goals, a major way of urban design is to encourage a modal shift from the use of private car to a lower-energy travel mode such as transit, cycling, or walking (Zajac 2016; Rietveld 2000; Cullinane and Cullinane 2005; Kwok and Yeh 2004; Mavoia et al. 2012). For example, the UK, US, and Australian governments have all encouraged the integration of land-use planning and transit-oriented design (Chow 2014; Benenson et al. 2010; Curtis 2012). Encouraging other travel modes over private transport and promoting intensive land use can also help maintain a more sustainable environment (Yang et al. 2017a, b). Therefore, comparing the spatial accessibility of different modes of transportation and detecting the modal accessibility gap (MAG) are thus useful methods of assessing the degree of low-energy travel mode development in the city (Kawabata 2008, 2009; Kawabata and Shen 2007).

In this vein, the present study measures the MAG between private and public transport from the mobility and proximity perspectives (Cervero 2005), which are important two aspects for sustainable transport and urbanism. The proposed approach uses the accessibility indicator, defined as the ability and ease to access places such as jobs, healthcare facilities, and public services and overcome friction such as distance and travel cost (Hansen 1959), which are considered to be potential opportunities for interaction. This accessibility definition includes two components: land use and the transport system. For the former, the more opportunities there are within a location, the higher is accessibility. For the latter, the lower the travel time cost from the origin to its opportunities (destinations), the higher is accessibility.

Regardless of the approach, the following problems must be addressed to ensure that accessibility can be examined. Firstly, origins and destinations must be defined. Here, origins are the centroid of the populated raster cells, while destinations are limited to commercial centers owing to space limitations in the paper. Secondly, travel time is frequently adopted because this is more appropriate than travel distances (e.g., Euclidian distance, Manhattan distance or Network distances) for the passenger trips (Fone et al. 2006; Larsen and Gilliland 2008). Thirdly, the calculation of time costs shouldn't ignore more essential components of journey (e.g., waiting, interchange and parking time). Finally, the potential attractiveness of a destination is habitually weighted by using features such as the scale (or number) of activities or jobs. In this paper, attractiveness is measured by using the size of commercial centers.

The remainder of this paper is structured as follows. Section 2 develops a "door-to-door" multi-modal travel network for measuring accessibility to destinations (i.e., commercial centers) and further calculating the MAG based on travel time and potential attractiveness, which are called the modal average travel time gap (T-MAG) and modal potential attractiveness accessibility gap (P-MAG)

herein. Section 3 introduces the study area and data sources. Section 4 analyzes the results of the patterns of the T-MAG and P-MAG distributions. Section 5 discusses the potential implications and suggestions for planning practices and traffic policies. Section 6 concludes this study and discusses future research.

Methodology

The MAG takes a few steps. The first is to estimate the travel times/distances from all the Origins to the Destinations in a multi-modal transport network with different travel modes; the second is modeling spatial accessibility to the destinations; finally, the calculation of the MAG between private and public transport.

Estimating Travel Times and Distances

The travel distances and travel times between origins and destinations are an essential part of accessibility analyses. However, using times may be superior as they not only reflect an accurate road distance/time (Haynes et al. 2006) but also associate with travel modes (Salonen and Toivonen 2013). Many studies estimate travel time by setting a minimum speed limits to each level of road and then using the O-D Matrix toolbox of ArcGIS to find the shortest travel route (Ni et al. 2015; Luo and Wang 2008). One disadvantage is therefore that the accuracy of the results depends on the manual setting speed. Moreover, the transportation network data available to individual researchers are often outdated (Yang et al. 2017a). To address these shortcomings, recent studies have employed the application programming interfaces (APIs) of map developers (e.g., Google Maps, Baidu Maps, Gaode Maps) to calculate travel time (Su et al. 2017; Yang et al. 2017a; Wang and Xu 2011). In this way, researchers can use the real-time transportation network information and routes of map developers to obtain realistic and reliable estimates of travel time and distance. In summary, travel time estimated by different methods may lead to diverse assessments of accessibility patterns.

This study used web-map-services APIs in Python to achieve more accurate estimates of travel time and distance for each O (Origin)-D (Destination) using the car, transit, and cycling modes, which is a door-to-door approach (Salonen and Toivonen 2013). Three independent APIs, namely the Transit Searching API, the Cycling Searching API, and the Driving Searching API, were developed to estimate travel times and distances separately for a normal weekday including rush hour and midday schedules and traffic conditions. In this paper, we estimated the door-to-door travel times and distances between origins (the 500-m populated raster cells provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences¹) and destinations (commercial centers according to the Urban Planning Bureau Nanjing²). The door-to-door routes were

¹ The population data set was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn>), regarding terrain and population density.

² See <http://www.njghj.gov.cn/>.

finally calculated based on the Searching APIs provided by a web-based service map developer (Fig. 1).

Transit Model

The Transit API considers the entire travel chains from an origin to a destination:

- Walking from the origin to a nearest bus stop or metro station
- Waiting at the bus stop or metro station
- Travel to the next bus stop or metro station
- Travel between mode changes
- Travel to the next (or final) bus stop or metro station
- Walking from the final bus stop or metro station to the destination

$$C_{ij} = C_{access} + C_{wait} + C_{in-vehicle} + C_{egree} \tag{1}$$

Car Model

The calculations for travel time were made for two time intervals of the day: peak and off-peak intervals. The door-to-door trip for car model includes:

- Walking from an origin to the parking place.
- Travel from the parking to another parking (including searching for a parking).
- Walking from the final parking to the destination

$$C_{ij} = C_{access} + C_{in-vehicle} + C_{parking} + C_{egree} \tag{2}$$

Cycling Model

The door-to-door approach for cycling routes includes:

- Walking from an origin to the cycling lot

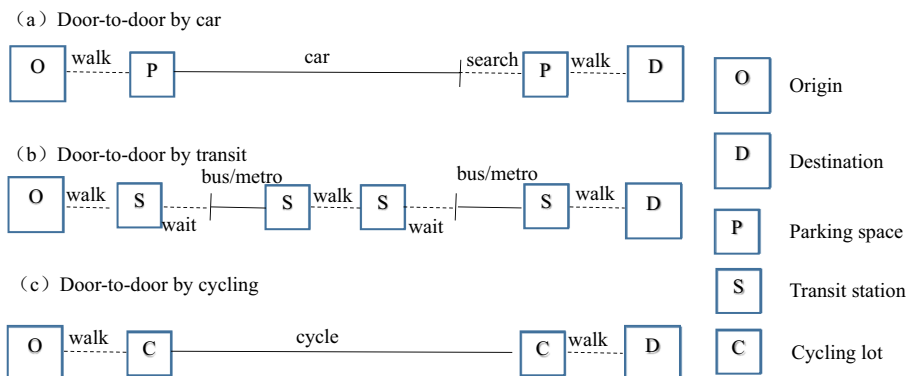


Fig. 1 The door-to-door travel routes for the (a) car mode, (b) transit mode, and (c) cycling mode

- Travel from one cycling lot to another cycling lot
- Walking from the final cycling lot to the destination

$$C_{ij} = C_{access} + C_{in-vehicle} + C_{egree} \quad (3)$$

Modelling Spatial Accessibility to Destinations

Nearest opportunity measure, Cumulative opportunities measures and Gravity-based measure of accessibility are popular in the previous literature (Páez et al. 2012). There is only one enough and available activity nearby (e.g., public library), Nearest opportunity measure approach may be more appropriate. On the other hand, for several activities (e.g., shopping centers, health facilities, restaurants), owning more nearby available choices, Cumulative opportunities measures and Gravity-based measure are more suitable. Both types of accessibility measurements require the travel distance/time cost data from origins to potential destinations and the number of opportunities across the study area. The main difference is the handling of distance/time factors: Cumulative opportunity measure takes dichotomy method to deal with decay function (see Fig. 2a), the areas are defined “accessible” within a pre-defined region (time/distance threshold) and completely inaccessible outside the threshold. It is often difficult to set an appropriate distance/time at which a service is no longer considered “accessible”. Gravity-based model overcome this pre-defined region assumption by incorporating notions of attraction and friction to estimate the propensity to travel to a particular location, and takes continuous decay function, considering the characteristics of facility service capacity attenuation with travel distance/time, but not limited the effective search radius (distance/time threshold) (see Fig. 2b).

Although all these methods requires a certain measure of distance/time, the travel distance/time from an origin to a destination differs by travel mode (i.e., it often takes a shorter time by car than by other travel modes). Meanwhile, the transport element alone cannot change the way in which people behave in accessibility analyses (e.g., their shopping choices), considering the attractiveness of the

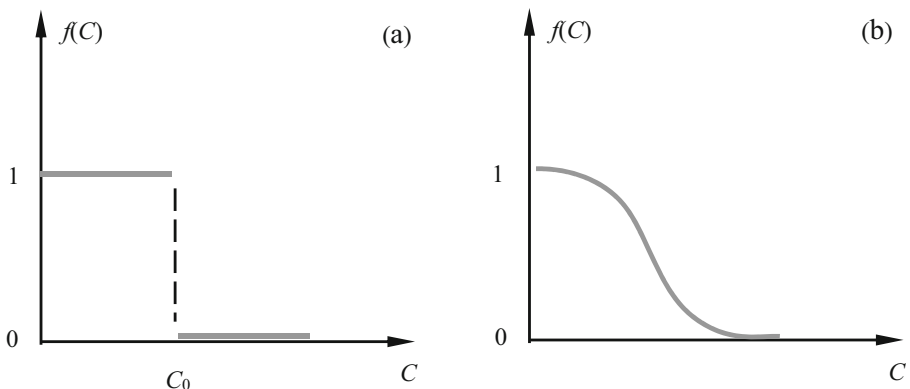


Fig. 2 Major forms of distance/time-decay function

business environment, which is another element that can significantly impact analyses. A large commercial center with a wide range of price concessions often encourages more consumers to choose better-known shopping centers to visit. To take account of the differences in mobility among multiple population groups and attractiveness of destination opportunities, the generalized accessibility framework should thus include these two aspects. Thus, we consider modified potential- or Gravity- model in this analysis.

Traditional potential accessibility can be measured in terms of travel distance/time and all the weighted places (destinations) contained by the study area over transport networks as follows (Páez et al. 2012; Handy and Niemeier 1997):

$$A_i^m = \sum_{j \in N} O_j \cdot f\left(C_{ij}^m\right) \quad (4)$$

where A_i^m is the potential accessibility index of the raster origin i with the travel mode m . O_j is the opportunities (e.g., commercial centers) available at the destination. C_{ij}^m symbolizes the travel cost by transport mode m from origin i to destination j by the shortest route (see Eq. (1), Eq. (2), and Eq. (3)). $f\left(C_{ij}^m\right)$ is the impedance-decay function of travel time between origin i and destination j .

The accessibility results obtained by using different decay functions may be diverse (Reggiani et al. 2014; Vries et al. 2004). In these literature, the gravity-model function has been commonly accepted as the distance-decay function, which has the advantage of calculated simplicity compared with other choices.

The distance-decay function f can be written as.

$$f(c_{ij}) = \begin{cases} C_{ij}^{-\gamma}, & C_{ij} \leq C_0 \\ 0, & C_{ij} > C_0 \end{cases} \quad (5)$$

where γ is the distance-decay coefficient and c_0 is threshold travel distance/time. However, γ is difficult to determine, and is often performed using 1 to 2 in the accessibility analysis. In addition, the delay function has a large attenuation in a short time (Vale and Pereira 2017). Hence, this study selects the gentler delay function for the accessibility analysis. The formulation is as follows:

$$f\left(C_{ij}^m\right) = \left(1 + \alpha^m \cdot \exp\left(-\beta^m \cdot C_{ij}^m\right)\right)^{-1} \quad (6)$$

where C_{ij}^m is also the travel time from i to j , mode m , while α and β are the parameters, which describes the generalized cost sensitivity of the people (our results are particularly sensitive to this parameter). The parameters were estimated for commuting time (see Fig. 3). We assumed that the commutes from an origin to a destination that takes 60, 45, and 30 min by the transit, cycling, and car modes would be 0.05, where the upper limit of decay coefficient is 1. The resulting estimates of the parameters using Eq. (6) were $\alpha^{Car} = 0.002402$ and $\beta^{Car} = -0.28727$ for the car mode, $\alpha^{Bicycle} = 0.004116$ and $\beta^{Bicycle} = -0.17955$ for the cycling mode, and $\alpha^{Transit} = 0.005258$ and $\beta^{Transit} = -0.113058$ for the transit mode.

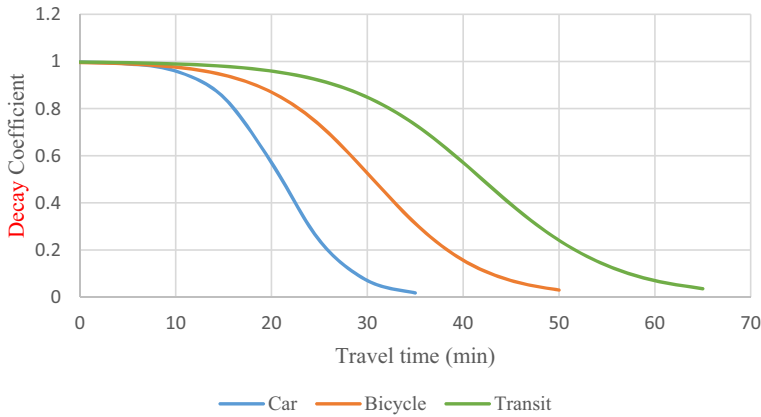


Fig. 3 Travel time-decay function

MAG Framework

To quantify the MAG between private and public transport, Kwok and Yeh (2004) proposed the following indicator:

$$MAG_i = \frac{A^P - A^C}{A^P + A^C} \quad (7)$$

where A^C respects the accessibility score of private transport and A^P respects the accessibility score of public transport. The MAG of all origins was scored from -1 to $+1$. A location with a MAG of -1 ($+1$) has no public (private) transport.

Scenarios

To examine the effects of multi-modal transport and opportunity accessibility in the generalized MAG model, two scenarios were developed and implemented according to the mobility and proximity perspectives.

Scenario 1: T-MAG

In the first scenario, we evaluate accessibility to destinations by using average travel time. Thus, all the raster cells are uniform regardless of the destination's attractiveness. The average travel time accessibility gap can be written as.

$$ATTA_i^m = \frac{\sum_{j \in N} c_{ij}^m}{N} = \bar{T}_i^m \quad (8)$$

$$T-MAG_i = \frac{\bar{T}_i^{public} - \bar{T}_i^{private}}{\bar{T}_i^{public} + \bar{T}_i^{private}} \quad (9)$$

where $\overline{T}_i^{private}$ is the travel time accessibility indicator of private transport and \overline{T}_i^{public} is the travel time accessibility indicator of public transport. The T-MAG of the origins was also scored from -1 to $+1$. The indicator equals to $-1(+1)$ means that travel time using public (private) transport is zero. (see Fig. 4).

Scenario 2: P-MAG

In the second scenario, the opportunity’s number or size is weighted to compute accessibility. Thus, compared with scenario 1, scenario 2 illustrates the effect on the accessibility results of using an additional variable (commercial centers’ areas) to estimate the attractiveness of the destination. The modal potential attractiveness accessibility gap can be written as follows (Fig. 4):

$$PAA_i^m = \sum_{j \in N} O_j \cdot f(c_{ij}^m) = \sum_{j \in N} O_j \cdot \left(1 + \alpha^m \cdot \exp(-\beta^m \cdot c_{ij}^m)\right)^{-1} = \overline{P}_i^m \quad (10)$$

$$P-MAG_i = \frac{\overline{P}_i^{public} - \overline{P}_i^{private}}{\overline{P}_i^{public} + \overline{P}_i^{private}} \quad (11)$$

where $\overline{P}_i^{private}$ is the potential attractiveness accessibility of private transport and \overline{P}_i^{public} is the potential attractiveness accessibility of public transport. The P-MAG of all origins was also scored from -1 to $+1$. A location with a P-MAG of -1 ($+1$) has no public (private) transport services (see Fig. 5).

Study Area and Data Sources

Study Area

The study area is Nanjing city, the capital of Jiangsu, an important city in eastern China. The population of Nanjing in 2016 was approximately 8.3 million people, and its GDP

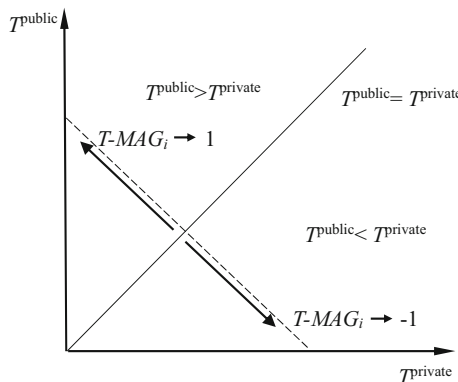


Fig. 4 The T-MAG between public and private transport

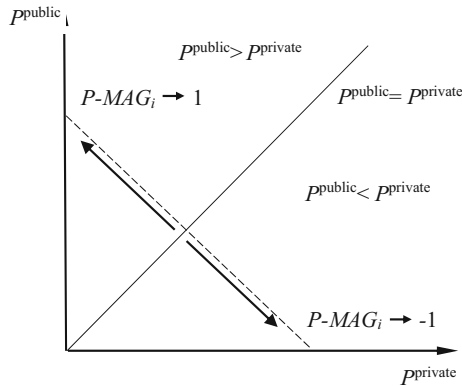


Fig. 5 The P-MAG between public and private transport

reached 10,503 billion yuan. There are 11 districts in Nanjing covering about 6582 km², which can be divided into three levels according to the Nanjing City Overall Plan (2015–2030): the central urban area, urban development area (also called the metropolitan region), and overall city area. The urban development area includes six urban districts (Gulou, Xuanwu, Qixia, Yuhuatai, Qinhuai, and Jianye), Jiangning district, Pukou district, most areas of Luhe district, and the Tuotang area of Lishui district, which is a highly urbanized area in Nanjing covering 4357 km². The central urban area includes the main urban district, Dongshan district, Xianlin district, and Jiangbei district, covering an area of 846 km². By contrast, the three districts in the urban development area are more developed and have closer socioeconomic connections (e.g., commercial services) with the central area (see Fig. 6).

Data Sources

To achieve the patterns of the MAG between public and private transport, we carried out a series of route analyses. We used the centroids of the populated raster cells as route origins in Nanjing. The routes' destinations were 58 most active public commercial centers in the city. The urban development area in Nanjing was divided into 7204 hexagons of equal size (see Fig. 7), which enabled us to measure accessibility equally (each arm of the hexagon was 500-m long, resulting in an area of each hexagon of 0.93 km²). The smallest administrative unit (street district) of Nanjing was 1.06 km².

The population data at the raster cell level were provided by the Data Center for Resources and Environmental Sciences at the Chinese Academy of Sciences.³ The population distribution map in Fig. 8 was created by combining the population data with their locations. In the following analyses of the accessibility gap results, the population corresponding to each hexagon was used. This distribution within the study area was modelled by using the 2010 population census of China (the lowest-level data aggregation unit in the China census), which was performed through land-use and remote population density interpolation. Hexagons were taken as minimal spatial units for the study.

³ See footnote 1.

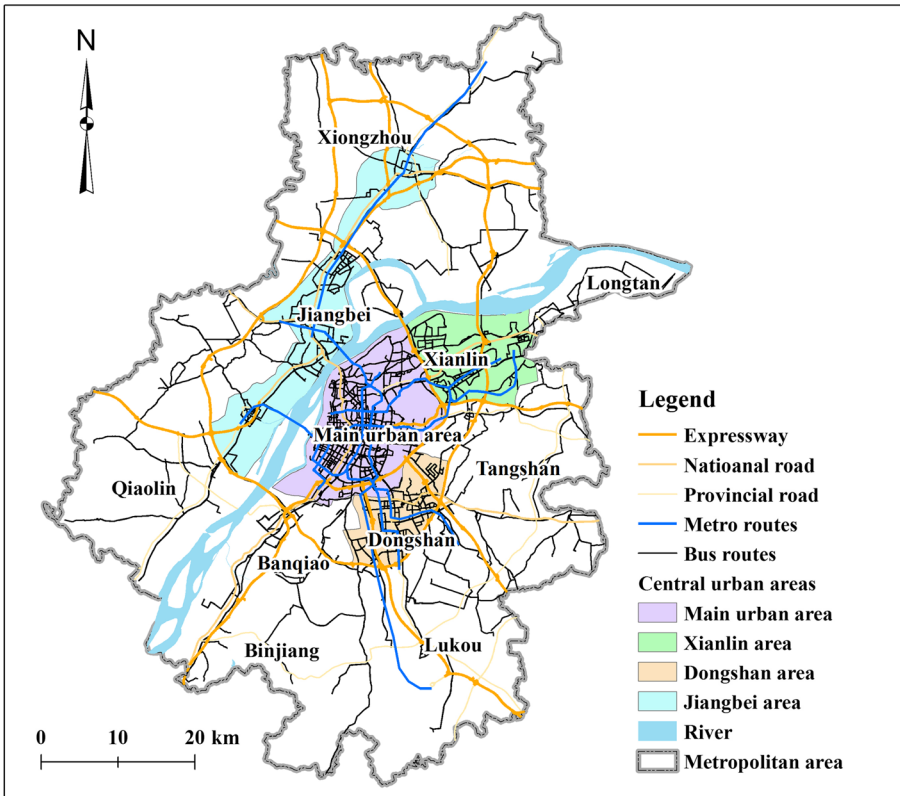


Fig. 6 Study area

In addition, the spatial distribution of the population was not sufficiently coordinated with the resources and environment in Nanjing. The agglomeration ability of the population in a new town was weak and the development pattern of the integration of industrial and urban areas has not yet taken shape. The economic development level is shown in the differences in infrastructure construction, basic public services, and social security between Jiangnan and Jiangbei (urban and rural areas).⁴

The locations of commercial centers were then overlapped onto the population map. In the following accessibility calculation, we used the scopes of the commercial areas as a component to represent their destination's service capability (or potential attractiveness) since this is one of the most important factors in attracting human capital to make transport options.

The data on commercial centers were taken from the website of Nanjing Municipal Planning Bureau (<http://www.njghj.gov.cn/NGWeb/Page/Index.aspx>). There are 74 commercial centers in Nanjing. Figure 8 shows their locations. Most commercial net sites (58 of 74) are located within the study area, highly concentrated in the central area of Nanjing. According to the Nanjing City Commercial Net Sites Layout Plan (2015–2030), the Xinjiekou, Hexi, Chengnan, and Jiangbei commercial centers are in the central urban area (class 1 in Fig. 8). There are seven municipal-level commercial

⁴ See <http://www.nanjing.gov.cn/>.

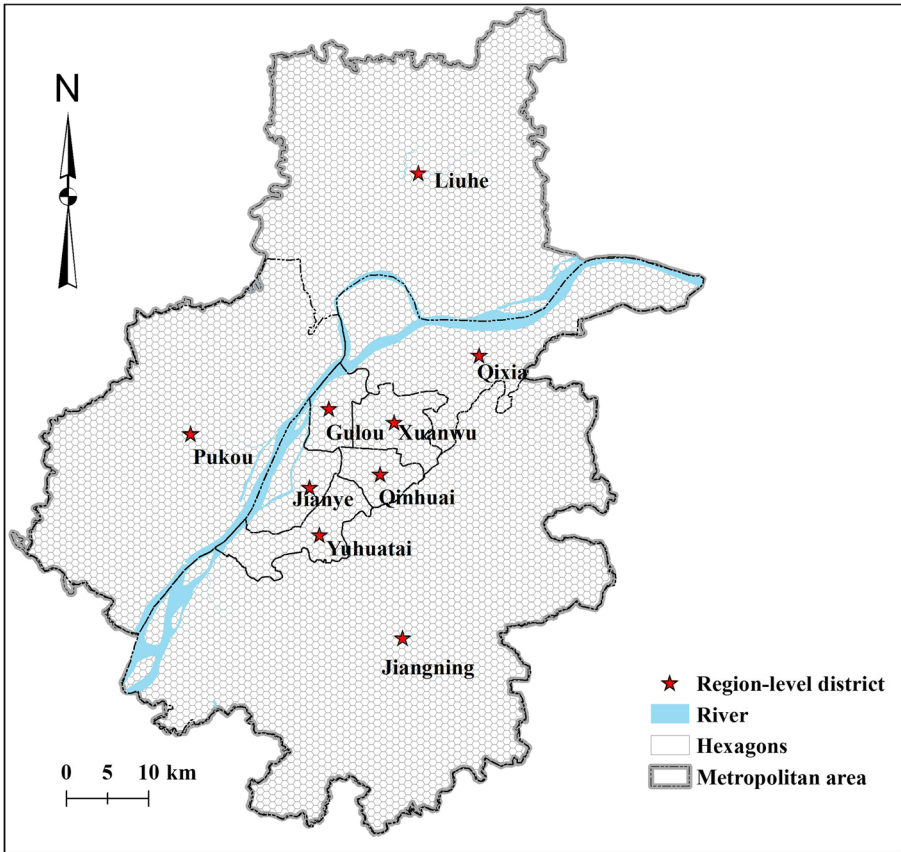


Fig. 7 The hexagon grid

centers (e.g., Hunan Road–Shanxi Road, Fuzhimiao), of which five are in metropolitan areas (class 2 in Fig. 8). There are 40 district-level and nine community-level commercial centers in the metropolitan areas (classes 3 and 4 in Fig. 8, respectively). The four

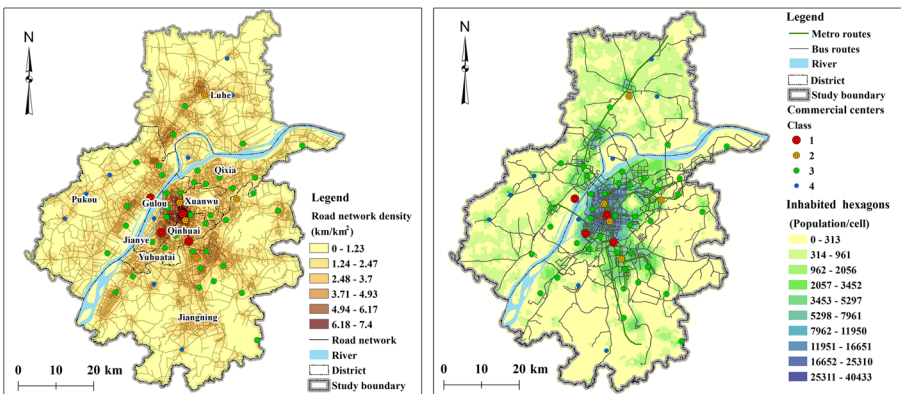


Fig. 8 Spatial distribution of the traffic network, commercial centers, and populated raster cells in the Nanjing metropolitan region

urban-level commercial centers (Xinjiekou, Jiangbei, Hexi, and Chengnan) form a gem-type commercial center structure.

Results

Figures 9, 10, 11 and 12 map the results of each scenario. These maps represent the MAG scores between public and private transport in peak and off-peak hours. Each map is illustrated by using the same classification and color scheme. Figures 9 and 10 show the results of the temporal pattern of T-MAG levels for the urban development area of Nanjing according to journey arrival times. Figures 11 and 12 visualize the P-MAG levels according to the journey arrival times and potential attractiveness of commercial centers. Tables 1, 2, 3 and 4 report the results of the two scenarios, using the accessibility gap indicator to capture the extent to which the transport system is appreciated (Eq. (9) and Eq. (11)).

Scenario 1: T-MAG between Public and Private Transport

A comparison of Figs. 9 and 10 suggests that the T-MAG scores reveal a similar pattern for both peak and off-peak hours. The coefficient of variation (CV = standard deviation/mean) is 0.0547 (0.0614) for off-peak hours and 0.0640 (0.0685) for peak hours between transit and car (cycling and car). Hence, the people living in central urban areas have a much smaller accessibility gap than those in distant suburban and rural areas. These findings confirm those previously described in the literature (Chen et al. 2017) and can be clarified by the concentration of road network density as well as the bus and metro routes in urban areas.

However, compared with Fig. 9b (corresponding 27% of the population ranges from 0 to 0.5000 in Table 1) and Fig. 10b (corresponding 24% of the population ranges from 0 to 0.5500) in off-peak hours, a considerable concentration of small T-MAG values shows a broader distribution in the central urban area in peak hours in Fig. 9a (corresponding 36% of the population ranges from 0 to 0.5000 in Table 1) and Fig. 10a (corresponding 26% of

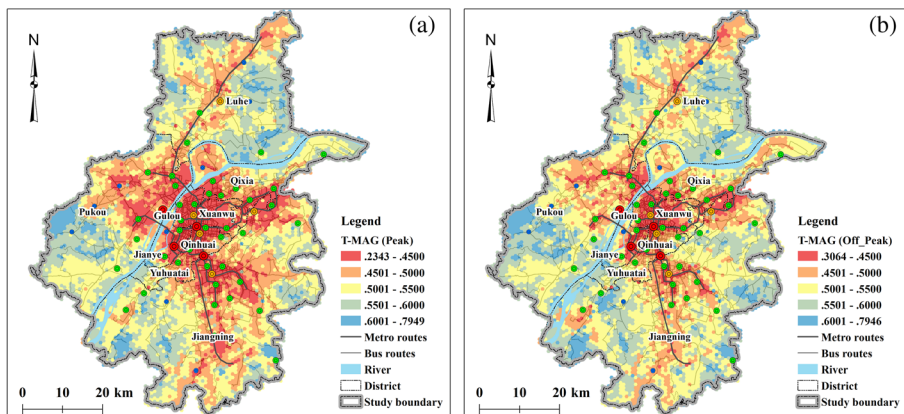


Fig. 9 T-MAG between car and transit shown in (a) peak hours and (b) off-peak hours

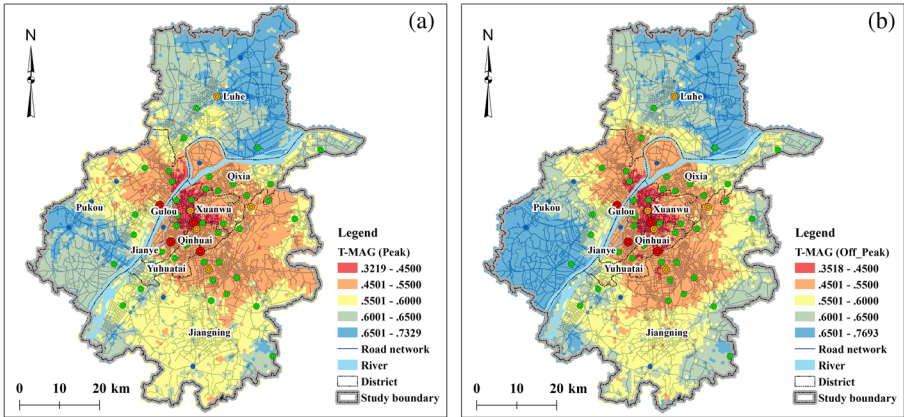


Fig. 10 T-MAG between car and cycling shown in (a) peak hours and (b) off-peak hours

the population ranges from 0 to 0.5500 in Table 2). This means that public transport is fairly competitive compared with private transport in peak hours.

The statistics for urban land uses in Tables 1 and 2 also indicate that transit (7% of the population in peak hours and 9% of the population in off-peak hours) ranges from 0.5501 to 1.0000 and cycling (14% of the population in peak hours and 15% of the population in off-peak hours) ranges from 0.6001 to 1.0000 (see the blue shading in Figs. 9 and 10). A possible reason is that these populations are located in the most distant areas outside the catchment areas of commercial services, meaning that those travelling by car can appreciate a wide range of commercial services.

The T-MAG scores increase significantly from the city center outwards as a result of the better traffic conditions (superior road network and higher frequency of public transport services), which may further strengthen the concentration during peak hours. Therefore, low destiny bus lines lead to a larger increase in T-MAG. As a result, accessibility to commercial centers by public transport for most raster populations reduces because of the decrease in competitiveness. Hence, the T-MAG model creates results that better reflect the barriers (e.g., traffic congestion and water region barrier) faced by passengers when accessing commercial centers.

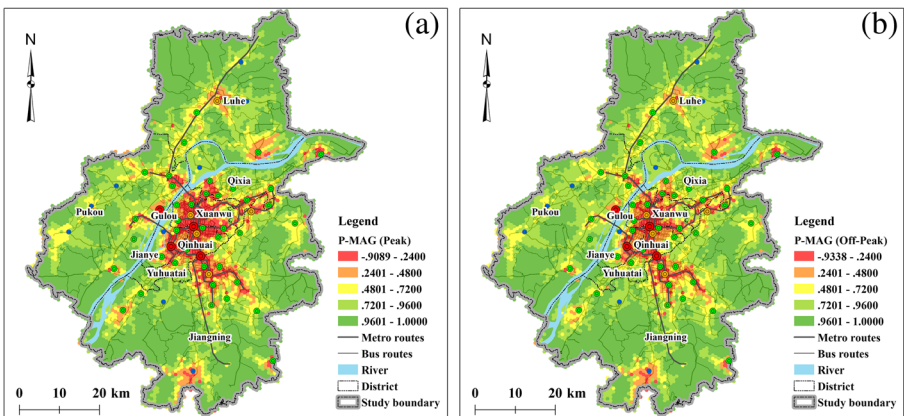


Fig. 11 P-MAG between car and transit shown in (a) peak hours and (b) off-peak hours

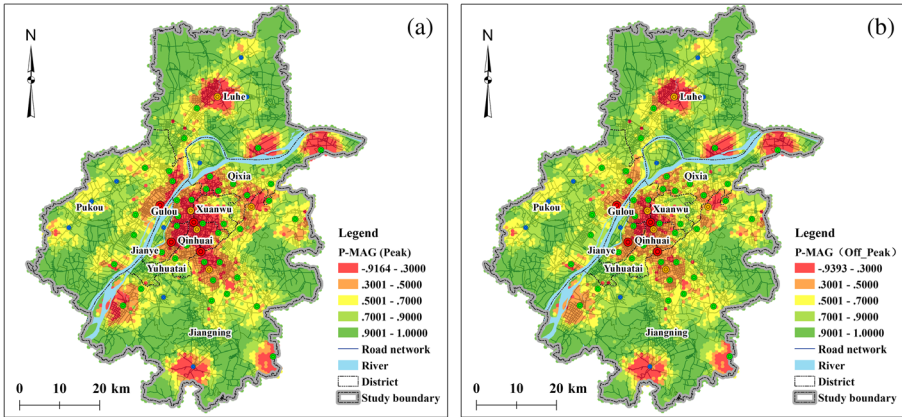


Fig. 12 P-MAG between car and cycling shown in (a) peak hours and (b) off-peak hours

Scenario 2: P-MAG between Public and Private Transport

Figures 11 and 12 show the P-MAG scores obtained for any origin raster cell. The raster cells in these map areas are grouped according to the natural break classifications generated by using ArcGIS. The areas with very low P-MAG, namely better accessibility by the transit or cycling modes, are shown in red, while the green shading corresponds to a larger MAG between public and private transport. The range of P-MAG values between transit and car is from $-0.9089/-0.9338$ to $1.0000/1.0000$ in peak/off-peak hours; some raster cells (the value range of P-MAG is $0.9601/0.9001$ to $1.0000/1.0000$ between cycling and car) are considered to offer disadvantageous access to commercial centers by transit/cycling.

Table 1 Descriptive statistics of T-MAG between transit and car in peak/off-peak hours

Transit	T-MAG Range	Peak				Off-Peak			
		N	Percent	Population	Percent	N	Percent	Population	Percent
	≤ 0.4500	1040	14%	4392753	62%	538	7%	2970629	42%
	0.4501–0.5000	1568	22%	1385933	20%	1391	19%	2092010	30%
	0.5001–0.5500	2295	32%	801069	11%	2588	36%	1386279	20%
	0.5501–0.6000	1793	25%	413605	6%	2099	29%	507921	7%
	0.6001–1.0000	508	7%	87455	1%	588	8%	123976	2%
Car		7204	100%	7080814	100%	7204	100%	7080814	100%

Table 2 Descriptive statistics of T-MAG between cycling and car in peak/off-peak hours

Cycling	T-MAG Range	Peak				Off-Peak			
		N	Percent	Population	Percent	N	Percent	Population	Percent
↑ ↓	<=0.4500	172	2%	1599773	23%	186	3%	2021223	29%
	0.4501–0.5500	1804	25%	3668947	52%	1557	22%	3479849	49%
	0.5501–0.6000	2282	32%	803804	11%	1791	25%	531474	8%
	0.6001–0.6500	1794	25%	665107	9%	1902	26%	557726	8%
	0.6501–1.0000	1152	16%	343183	5%	1768	25%	490542	7%
Car		7204	100%	7080814	100	7204	100	7080814	100%

The P-MAG scores for access to commercial centers nearby are lower for short distances and higher for long distances, meaning that transit/cycling is fairly competitive compared with the car mode. Other areas of low P-MAG scores are found along metro or bus lines (Fig. 11) or the higher road network destiny in the central urban areas (Fig. 12). The largest P-MAG scores are concentrated along the edges of the study area away from commercial centers, indicating that traveling from these areas to the destinations is much slower than traveling by transit/cycling. The P-MAG scores between car and transit/cycling weaken in peak hours, meaning that the latter modes become more advantageous

Table 3 Descriptive statistics of P-MAG between transit and car in peak/off-peak hours

Transit	P-MAG Range	Peak				Off-Peak			
		N	Percent	Population	Percent	N	Percent	Population	Percent
↑ ↓	<=0.2400	408	6%	2916751	41%	280	4%	2021684	29%
	0.2401–0.4800	467	6%	1160562	16%	445	6%	1598165	23%
	0.4801–0.7200	844	12%	1116045	16%	839	12%	1330337	19%
	0.7201–0.9600	1913	27%	1118599	16%	2015	28%	1329566	19%
	0.9601–1.0000	3572	50%	768857	11%	3625	50%	801062	11%
Car		7204	100%	7080814	100%	7204	100%	7080814	100%

Table 4 Descriptive statistics of P-MAG between cycling and car in peak/off-peak hours

Cycling	P-MAG Range	Peak				Off-Peak			
		N	Percent	Population	Percent	N	Percent	Population	Percent
↑ ↓	<=0.3000	685	10%	2985010	42%	420	6%	1454531	21%
	0.3001-0.5000	767	11%	1552246	22%	779	11%	2366220	33%
	0.5001-0.7000	1290	18%	1140312	16%	1299	18%	1536697	22%
	0.7001-0.9000	1622	22%	832338	12%	1802	25%	1134801	16%
	0.9001-1.0000	2840	39%	570908	8%	2904	40%	588565	8%
Car		7204	100%	7080814	100%	7204	100%	7080814	100%

as a result of the increasing driving time/cost caused by congestion. Regarding the overall P-MAG distribution, transit/cycling offers better (worse) competitiveness in peak (off-peak) hours.

To make our results easy to interpret, we report the levels of P-MAG regarding the percentage of the population and raster numbers that experience them (see Tables 3 and 4). These tables show that most residents have high reliance on the car mode to travel to commercial centers, with more than 50% of the raster cells between transit and car having high accessibility and less than 11% having low accessibility to such spaces (P-MAG > 0.9600). Moreover, more than 40% of the population of raster cells between cycling and car had high accessibility and only less than 8% of the population had low accessibility to such spaces (P-MAG > 0.9000). However, Tables 3 and 4 show that both peak and off-peak hours produced distinct P-MAG scores in central urban areas, but similar ones in rural areas. Figures 11 and 12 shows that for a range from 0 (0) to 0.2400 (0.3000) between transit and car (cycling and car), the peak hours produced P-MAG scores higher than the off-peak hours by 12% (21%). By contrast, for a range from 0.9601 (0.9001) to 1.0000 (1.000), the off-peak hours showed no change in the P-MAG scores for both raster cell numbers and population. To explain the above-mentioned patterns, we revealed the difference from peak and off-peak hours using scatterplots (Fig. 13) because people seek commercial services in peak hours by the transit mode. Then, more people have access to commercial centers and compete for a certain number of services by transit, resulting in a larger proportion. The off-peak hours reduced the number of passengers who choose public transport for a certain number of services.

Comparative Analysis of Scenario 1 and Scenario 2

The higher density of metro and bus routes helps decrease the T-MAG patterns in Figs. 9 and 10, while the location and attractiveness of commercial centers

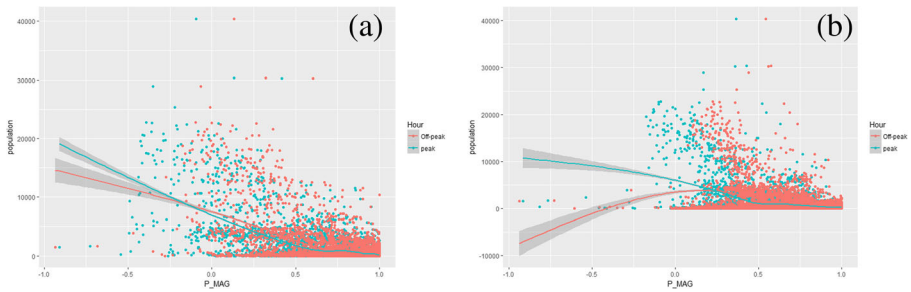


Fig. 13 Scatterplot of the P-MAG scores with (a) transit vs. car and (b) cycling vs. car between peak and off-peak hours

help decrease the P-MAG patterns in Figs. 11 and 12. However, while these empirical findings were significant as the P-MAG value was lower, they were less obvious as the P-MAG value increased (see Figs. 13 and 14). A potential reason for this finding is that in off-peak hours, people travel to commercial centers by car, thus rising their competence to access such areas. Hence, for the majority of raster cells, peak hours resulted in a lower accessibility gap than off-peak hours did. The foregoing analysis suggests that the analysis of the sustainability of urban transport should also include the location and service capability of the destination as well as the impact of traffic conditions when planning and allocating resources in practice.

Discussion

Our analysis showed that public transport is advantageous at certain times of the day (peak hours) and for certain corridors (transit routes), but disadvantageous when competing with private transport because of the longer travel time to destinations. Moreover, the disadvantage of public transport is more serious in periphery areas, especially far from metro stations and bus stops. For instance, lower bus frequencies leads to longer waiting times and transfer times at the bus stop during off-peak hours. The disadvantage of the cycling mode in Jiangbei district is because of the effect of the Yangtze River and cross-river channel. Therefore, improving the public transport infrastructure and constructing more cross-river bridges would help increase sustainability as in Pukou district and Luhe district. Similarly, new building residential and commercial land should be considered near to metro station or bus stops in order to be more convenient to access reducing car dependence to improve transport sustainability.⁵

In future planning, the Jiangbei New District (including Pukou district and Luhe district) will optimize the layout of the transportation infrastructure and speed the construction of the cross-river channel to promote the construction of transport hubs such as Nanjing North Station and Xibai Port, where the MAG will be reduced in the central urban area. Further, the location and attractiveness of the opportunities affect the MAG since these are located close to the public transport

⁵ See <http://www.njghj.gov.cn/>.

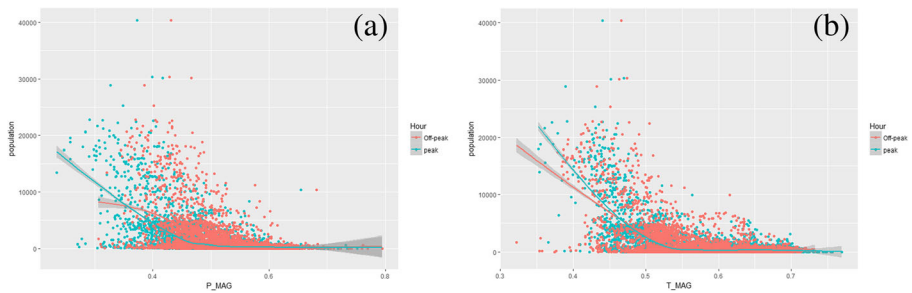


Fig. 14 Scatterplot of the P-MAG scores with (a) transit vs. car and (b) cycling vs. car between peak and off-peak hours

infrastructure. However, owing to the more difficult access by private car, this will further improve accessibility by public transport and cut the MAG between public and private transport. Therefore, a planning strategy of locating opportunities close to public transport, especially near the transit interchange, will favor sustainable transport development. Since the span of a public transport network is usually smaller than that of private transport, this development strategy would also mean a higher density and centralized land-use pattern.

Similar to our results, the Commercial Network Planning (2015–2030) and Integrated Transportation System Planning During the “13th Five-Year” Period in Nanjing propose redistributing commercial resources from central areas to periphery areas by, for example, relocating existing commercial centers or building new branches in periphery areas. Adjusting the core function area, building new metro routes, and promoting the city’s new districts in Jingbei will further improve and optimize accessibility and enhance sustainable traffic development, decreasing reliance on cars in Nanjing. Further, the population can be moved to areas of good public transport accessibility, since the location of homes and commercial facilities also affects accessibility to commercial centers when using low-energy travel modes.

Overall, the spatial accessibility gap between central urban areas and periphery areas is uneven. The T-MAG in periphery areas is much larger than that in central areas. A serious effort should thus be made to improve the efficiency of public transport by providing pedestrians with suitable cycling facilities. For instance, bicycle-sharing schemes are gaining popularity in many Chinese cities including Nanjing (Fig. 15), as they provide an effective means of accessing metro stations. Such schemes have the potential to substantially improve accessibility if suitable public service facilities are made available at metro stations and safe cycling routes are integrated into the city’s road network.

Figure 15 also illustrates that the transit+cycling scenarios may be more dominant in making accessibility changes than the transit+walking scenarios. Hence, Nanjing’s bicycle-sharing scheme will play a significant part in raising metro station access and, to a lesser extent, station egress as in other large cities. Overall, the MAG indicators could aid decision-making by planners and officials on land-use and transport systems. For example, the MAG patterns analyzed in Figs. 9, 10, 11 and 12 are useful to help develop residential and industrial areas, especially if the study is estimated at the smaller scale and takes account of more transportation modes.

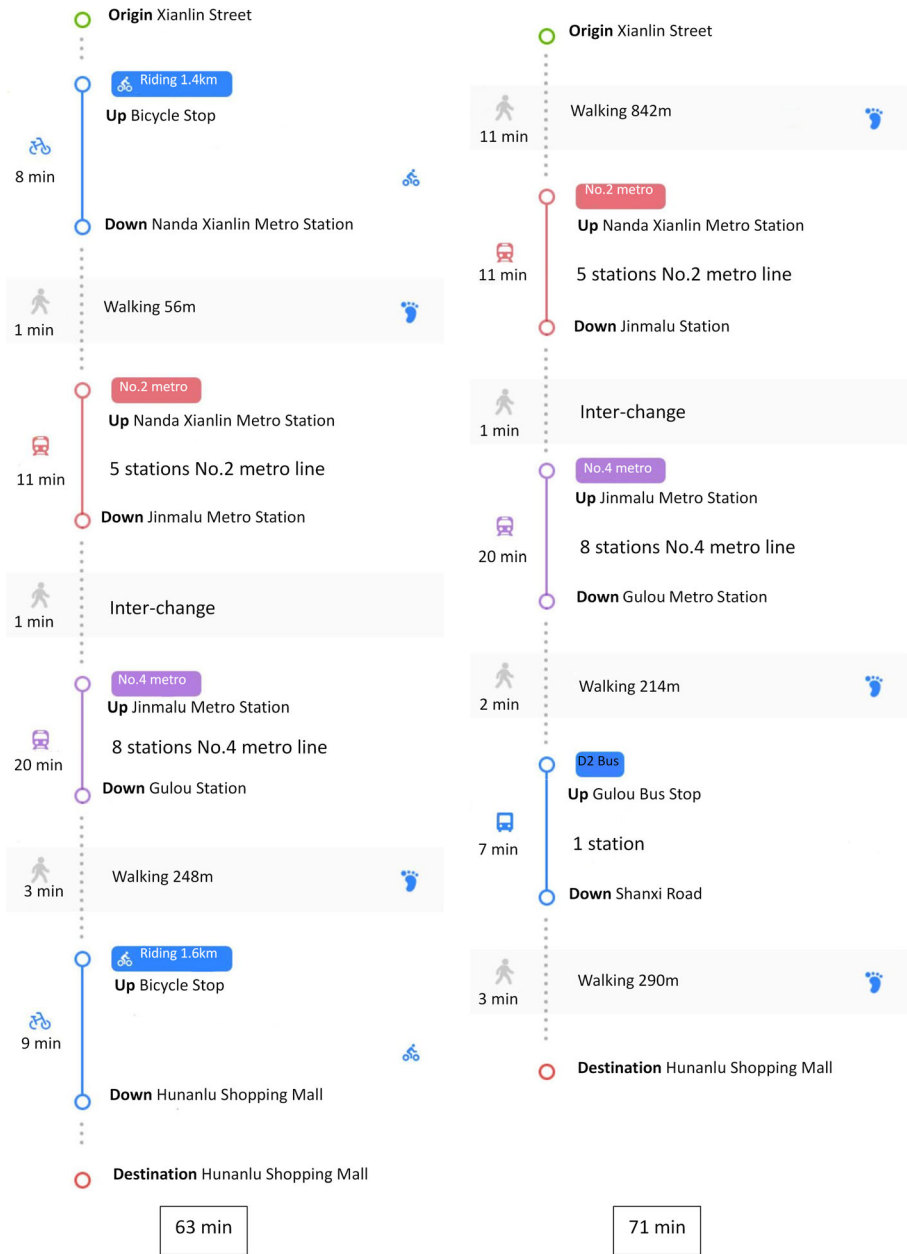


Fig. 15 Examples of the door-to-door approach in (left figure) transit+cycling and (right figure) transit+walking journeys

Conclusion

This study measured the accessibility gap between more energy-efficient and less energy-efficient transport modes based on web-based map services in Nanjing.

These newly available data sources make it possible to estimate accessibility for any location, thus the scope of the gaps between private and public transport accessibility across the metropolitan area in Nanjing. The “door-to-door” model adopted in this study also provides a realistic and truthful estimation of accessibility by incorporating more individual travel behavior into the generalized MAG framework. The mode competition is modeled as the different level of access to destinations in terms of mobility and proximity. A case study was finally carried out by comparing the transit/cycling mode with the car mode to find the degree of sustainable transport development in Nanjing. The MAG can thus serve as a sustainable indicator to estimate different transport developments and land-use plans.

Several conclusions and policy implications from the analysis can be drawn:

- For substantial trips, travel times by the transit/cycling mode are longer than those by car;
- Access to destinations by car is characterized by a high degree of variability compared with real-time conditions in peak and in off-peak hours;
- Between transit and car, the raster cells with low T-MAG scores are mainly concentrated in the central urban area and nearby metro stations and bus routes, while the raster cells with high T-MAG scores are commonly scattered in rural fringe areas away from metro stations and bus stops;
- The overall impacts of the density of metro and bus routes are constructive, suggesting that building more such routes is an effective way in which to decrease the T-MAG;
- For multi-modal transit trips, the pedestrian connection could increase the accessibility of public transport to a certain extent. Therefore, raising the number of shared bicycles would improve accessibility and thus lessen the difference with the car mode; and
- The location and attractiveness of the opportunities could affect the P-MAG if these are located close to the public transport infrastructure in areas. This would ultimately improve the accessibility advantage of public transport and lower the P-MAG scores.

However, the application of this multi-modal model is more far-reaching. The proposed model can be applied in other situations with varied population groups (e.g., people with different incomes or immigrants). It can also serve as a foundation for the consideration of other factors influencing competition for public services among population groups in future work. For example, the distance-decay coefficient or even function is diverse for different modes, and this needs to be further examined based on survey datasets derived from census data and travel behavior surveys.

There are some limitations that need to be mentioned. The first limitation is the raster-level population data using 2010 census data, whereas the online crawled routes between origins and destinations computed are written in the

Python programming from 2018. The premise of this paper is that the population has not changed greatly. Another important limitation is the effect of resolution of the raster cell scale. The equally-sized (500-m in this paper) hexagon was adopted for the study area in Nanjing. However, taking into account the actual origins, routes and destinations for travelers, the optimal raster resolution may need to be further analyzed.

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Compliance with Ethical Standards

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