



Evaluating multiscale and multimodal transport inequalities in Chinese cities with massive open-source path data

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Abstract

Accessibility is an effective variable for identifying mobility needs and evaluating transport inequalities. In recent years, the construction of transport facilities has been often considered to have a significant effect on the accessibility of cities. This study focused on the regional inequalities of transport accessibility in China and the influence of transport mode disparity. A novel approach integrating intercity and intracity transport networks is modeled for detailed calculations of travel time using open-source massive path data. The proposed approach provides further improvement in the accuracy, and it can reflect realistic patterns of multiscale accessibility. Four indicators based on travel time estimation were employed to evaluate transport accessibility and inequality: weighted average travel time (WATT), potential value (PV), daily accessibility (DA), and coefficient of variation (CV). Results show that transport accessibility is the highest in the eastern region, followed by the midland, northeastern, and western regions; this trend is consistent with the level of urban development and transport facilities construction. The inequality of transport accessibility between cities is obvious, and the western region has a considerably greater inequality than other areas. With regard to transport facilities, the car driving mode has higher accessibility and lower discrepancy than the public transit mode at the national level; however, the construction of public transit infrastructure, especially the high-speed railway, should considerably improve the daily accessibility of cities. Several policy suggestions are provided for transport departments and decision makers that can effectively improve the level and equality of transport accessibility of cities in China.

Keywords Inequality · Multiscale accessibility · Multimode transportation · Open-source massive path data · China

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1 Introduction

Poor access to opportunities and services provided by cities is a major obstacle to improving livelihoods and development (Weiss et al. 2018). Accessibility, defined as the difficulty for an individual to reach a destination via any transport mode, is a critical indicator for measuring economic development, social welfare, employment opportunities, environmental resources, and land use availability of cities (Martin et al. 2002; Lambin et al. 2006; Richardson et al. 2013; Schwanen and Wang 2014).

Many scholars have studied transport geography in terms of accessibility, and the effect of transport infrastructure on regional equality and been investigated at length. The research scale ranges from international, national, provincial, economic zone, metropolitan to county units. At the county scale, Hess (2005) compared the number of jobs accessible via automobile versus public transit in Erie and Niagara Counties of the western New York State. Gutiérrez and Gómez (1999) discussed the effect of rail traffic on inter-metropolitan transport accessibility. Singh and Sarkar (2022) measured accessibility to opportunities of rural districts in India. At the national scale, Stelder (2016) analyzed the European road network for the period 1957–2012 and found that peripheral regions lost accessibility at first; however, they have been catching up since 1990. Kim (2000) and Kim and Sultana (2015) researched the disparity of accessibility growth for cities along major Korean high-speed railway (HSR) corridors in different periods. Their results suggested that HSR construction may increase inequalities in accessibility because of uneven regional development. Otsuka (2017) studied the relationship between a high-speed transport network and the economies of agglomeration in 47 Japanese prefectures, and the results confirmed the effect of accessibility on the development of the Greater Tokyo area. At the international scale, Weiss et al. (2018) quantified the travel time to cities around the world and discussed relations between accessibility and wealth, education, and healthcare utilization. Their results showed that, although exceptions exist, there is an undeniable association between accessibility and human well-being in low-to-middle income countries.

Accessibility comprises four critical components: land use, transportation, temporal, and individual (Geurs and van Wee 2004). For practical applications, accessibility is measured by focusing on one or several components (Geurs and van Wee 2004; Geurs et al. 2015). Geurs and van Wee (2004) describe four aspects for measuring accessibility: (i) *Infrastructure-based* measures, measuring the (observed or simulated) performance or service levels of transport infrastructure; (ii) *Location-based* measures, measuring accessibility of distributed activities on an aggregate level; (iii) *Person-based* measures, measuring accessibility at the individual level, which is founded in the space–time geography of Hägerstrand that incorporate individual mobility and time budgets (Hägerstrand 1970); and (iv) *Utility-based* measures, measuring the cost effectiveness that people derive from access to the spatially distributed activities.

In the field of transport geography, the concept and measurement of transport accessibility indicates the difficulty in interactions between cities (Johnston 1994). Existing literature indicates that travel time calculation is key to accessibility analysis. Some improved methods based on vector topological structure and raster analysis using standard geographic information system (GIS) software have been proposed (Pérez et al. 2011; Salonen and Toivonen 2013; Wang et al. 2017; Weiss et al. 2018). Travel time calculation for vector data often includes four steps:

- (1) Simplify every location or region as a point and build an origin–destination (O–D) matrix by connecting every point, where the connecting lines represent traffic connections.
- (2) Assign weights and speeds to each edge based on the priority and importance of traffic connections and individual preferences for opportunities at the destination.
- (3) Obtain the optimal path with algorithms such as graph search.
- (4) Calculate the speed along each optimal path and add the time cost of the line.

However, the conventional method of modeling travel time has the following drawbacks: The extensively used standard GIS software is incapable of integrating official up-to-date transit and railway schedules directly into road networks (Lei and Church 2010); studies that only consider static time often ignore time changes caused by variations in roads, traffic conditions, transfer between vehicles, and so on (Moya-Gómez et al. 2018; Farber and Fu 2017). The conventional method is biased to representing the accessibility of an entire city or that among cities using only a single traffic mode at one traffic connection, without considering the diversity of traffic modes (Wang et al. 2016; Zhang et al. 2018).

Big data sources, e.g., internet navigation maps, offer more detailed transport information including public transit schedules, true travel speed on roads, etc. It improves the veracity of travel time calculation, especially for intercity journeys by public transit, of which waiting time varies greatly between schedules. The literature review uncovers many works that have investigated the effects of transport accessibility in China (Zhang and Lu 2007; Jin et al. 2013; Jiao et al. 2014; Wang et al. 2016; Zhang et al. 2018), while few of them have applied such new data sources in travel time calculation for multimodal intercity accessibility studies.

In this study, a multiscale accessibility measure–multimodal travel time integrating intercity and intracity transport networks based on open-source massive path analysis (OMPA)–was modeled to evaluate the transport inequality of cities on the Chinese mainland. OMPA provided by internet mapping service was used for efficient and accurate calculation of multimodal travel time. With OMPA, this paper tries to delineate regional accessibility inequality in China and to study inequality for different transportation modes, from which reflects inequality of the transportation system in some degree.

The remainder of this manuscript is organized as follows: Section 2 presents the study area. Section 3 provides the accessibility indicators and the principle

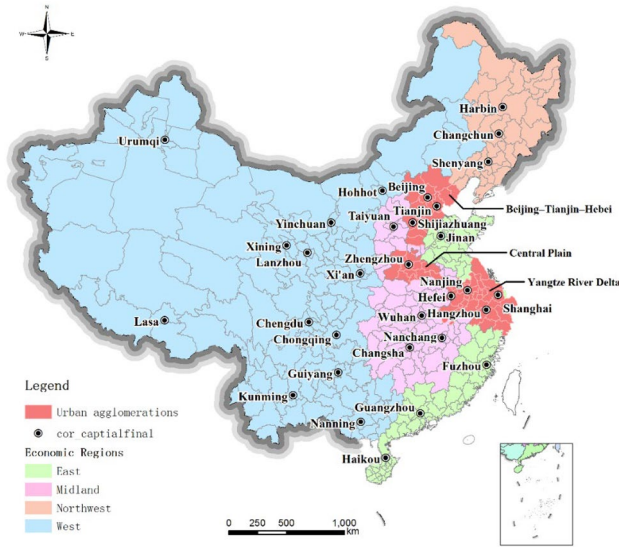


Fig. 1 Economic regions in mainland China

and details of the OMPA method. Section 4 describes the accessibility inequalities in municipalities and prefecture-level. Section 5 discusses the transportation inequalities for different modes, and further discusses inequalities of transport infrastructure. Section 6 presents the discussion by comparing to previous works and addressing research limitations, followed by conclusions and policy suggestions.

2 Study area

For this study, 3185 cities of mainland China (excluding Sansha, Hong Kong, Macao, and Taiwan) were considered as the study area; this included four municipalities, 333 prefecture-level divisions, and 2848 county-level divisions.¹ Municipalities and prefecture-level (M&PL) divisions were treated as the research subject, and county-level (CL) divisions were regarded as accessible regions from M&PL. Statistical analysis was conducted on a M&PL-scale for delineating regional inequalities. Accessibilities of M&PLs were calculated on a finer CL-scale for involving both urban and rural area.

All cities were classified according to the economic region in which they were located: 88 (26.1%) M&PLs in the eastern region, 82 (24.3%) in the midland, 36

¹ In the Chinese administrative division system, the four municipalities are under the direct control of the central government (i.e., Beijing, Tianjin, Shanghai, and Chongqing). A prefectural-level division ranks below a provincial-level division and above county-level divisions.

(10.7%) in the northeastern region, and 131 (38.9%) in the western region (Fig. 1). The population and gross domestic product data were collected from the 2015 China Statistical Yearbook² and 2015 China City Statistical Yearbook.³

3 Methodology

3.1 Selection of indicators

This study considered two elements of transport accessibility: time and opportunity. The time cost determines the amount of area an origin city i can reach, and opportunity represents the attraction of origin city i . Based on travel time calculations, three classical indicators were used to evaluate transport accessibility: weighted average travel time (WATT), potential value (PV), and daily accessibility (DA). These three indicators were used for evaluating accessibility in different aspects. WATT is the travel time cost weighted by the destination's gravity. DA is population that can be reached within a certain travel time limit. Neither WATT nor DA considers declining effects of travel time. PV considers both destination's gravity and declining effects of travel time. The coefficient of variation (CV; standard deviation divided by the average) and weighted CV were also applied to evaluate the inequalities of transport accessibilities between cities.

3.1.1 Weighted average travel time (WATT) indicator

To determine accessibility, topological length and minimum cost between two nodes must be calculated (Maćkiewicz and Ratajczak 1996) to measure the connectivity of the transportation network. WATT represents the average travel time from one node to all other nodes when weighted by the mass distribution of destinations. WATT is calculated as

$$\text{WATT}_i = \frac{\sum_{j=1}^n \left((T_{ij}^k)^\beta \times M_j \right)}{\sum_{j=1}^n M_j} \quad (1)$$

where T_{ij}^k is the travel time between nodes i and j via travel mode k , and β is the rate of increase in the friction of travel time. In this case, T_{ij}^k was calculated by the travel time from M&PL i to CL j (i.e., location of the government) by travel mode k . M_j is the mass of node j , which is calculated by the square root of the product of the population and GDP of node j (Gutiérrez 2001). M_j is a square root to avoid too much effect caused by high values of population or GDP. M_j is expressed as

² <http://www.stats.gov.cn/tjsj/ndsj/2015/indexch.htm>.

³ <http://tongji.cnki.net/kns55/navi/YearBook.aspx?id=N2016030128&floor=1>.

$$M_j = \sqrt{P_j \cdot G_j} \quad (2)$$

where P_j is the population of node j and G_j is the GDP of node j . In this case, node i refers to M&PL, and node j represents CL.

3.1.2 Potential value (PV) indicator

Another measurement of accessibility is the relationship between the purposeful activities and distance. It is defined by PV, which measures the proximity of potential economic activities to a particular node, and it accounts for possible interactions between nodes by using the distance decay (Joseph and Bantock 1982; Gutiérrez and Gómez 1999; Martín et al. 2004). PV can be represented as

$$PV_i = \sum_{j=1}^n \frac{M_j}{(T_{ij}^k)^\beta} \quad (3)$$

where PV_i is the potential accessibility of node i . T_{ij}^k and M_j are the same as in Eq. (2).

3.1.3 Daily accessibility (DA) indicator

The DA can be used to calculate the population or economic activity that can be reached from every node within a certain travel time limit on the same day (Martín et al. 2004). The DA measures the population (Wang et al. 2016) that can be reached within a time limit. It is calculated as

$$DA_i = \sum_{j=1}^m V_j \delta_{ij} \quad (4)$$

where DA is the accessibility of M and PLs, m is the number of CLs, and V_j is the population of CL j . δ_{ij} is equal to 1 if T_{ij}^k is less than the time limit; otherwise, δ_{ij} is equal to 0. T_{ij}^k is the travel time between the location of the government in M and PL i and CL j using the travel mode k . In this case, if the location of the government of CL j can be reached from the government of M and PL i within the time limit, CL j can be concluded to be accessible for M and PL i .

DA can also be used to construct isochrones. When the time limit changes, DA will change accordingly and become a “certain time accessibility.” With DAs under various time limits, isotime contours can be mapped to express urban time structure.

3.1.4 Coefficient of variation (CV) and weighted CV

The CV was used to measure the disparity of accessibility among M&PLs (Gutiérrez 2001; López et al. 2008; Monzón et al. 2013); it can be used to evaluate accessibility

inequalities among cities, which is helpful for understanding and comparing accessibility inequalities caused by spatial locations. CV is expressed as

$$CV = \frac{\sigma}{\mu} \quad (5)$$

where σ is the standard deviation of values for each accessibility indicator and μ is the corresponding average of σ .

Weighted CV evaluates regional inequalities with population as weights. It is expressed as

$$CV_w = \frac{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \times \frac{V_i}{\sum_{i=1}^n V_i}}}{\bar{x}} \quad (6)$$

where x_i is the accessibility indicator of M&PL i and \bar{x} is the average. V_i is the population of M&PL i .

Both CV and weighted CV were evaluated at national and regional scale. Accessibility indicator values of M&PLs inside the country/region were used to calculate the national/regional CV and weighted CV.

3.2 Approach to measuring travel time

Travel time is an essential and reliable indicator of accessibility because it considers the temporal factor of actual traffic conditions and reflects the difficulty of travel between two regions (Maćkiewicz and Ratajczak 1996; Martínez Sánchez-Mateos and Givoni 2012; McKenzie 2014). In standard GIS software, network analysis is provided to calculate the travel time; the shortest path algorithm is used to search the optimal path from the origin to the destination. The problem with this method is that it only considers constant time for each path; it ignores variations for different path segments (O'Sullivan et al. 2000; Liu and Zhu 2004; Lei and Church 2010) and the time spent on transfers, including walking to another vehicle station and waiting for departure (Mavoa et al. 2012; Tribby and Zandbergen 2012). In addition, other factors that may change the travel time of urban traffic, such as traffic jams, time cost for parking, and walking time from a parking space to a destination (Christie and Fone 2003; Yiannakoulias et al. 2013).

3.2.1 Multimodal travel time calculation

For a precise analysis of each phase of a travel trip, a realistic door-to-door multimodal approach (Benenson et al. 2011; Salonen and Toivonen 2013; Wang et al. 2016) was used to determine the travel time from M&PL to CL by linking the intercity and intracity networks.

For a realistic multimodal transportation journey, two conditions are considered: (1) driving from the origin to the destination, where the entire journey occurs on the

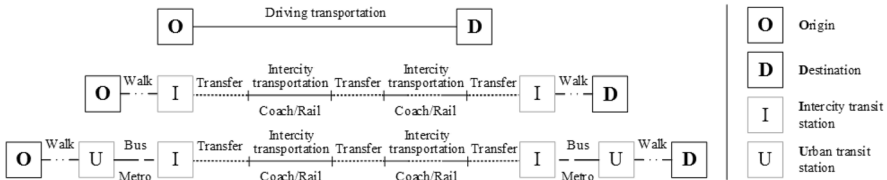


Fig. 2 Multimodal transportation journey (Chen et al. 2018)

road (R); (2) and using public transit, which includes several segments such as walking to the bus/metro stop, accessing the coach/railway station by urban public transit, waiting at the station, taking an intercity journey to another division by coach or railway (including transfer), getting off the intercity transit vehicle, and heading for the destination by walking or via urban public transit. Thus, the public transit journey can be expressed as intercity public transit (coach or rail) + walking (IPTW) and urban public transit (bus or metro) + intercity public transit (coach or rail) + walking (UIPTW). The intercity public transit stage may contain several legs, for instance, transition from coach to rail, from rail to coach, etc. Figure 2 illustrates the multi-scale transportation journey.

The travel time of a multimodal transportation journey can thus be calculated as

$$T_R = T_{OD}^{car} \tag{7}$$

$$T_{IPTW} = T_{OI} + T_{II} + T_{ID} + T_t \tag{8}$$

$$T_{UIPTW} = T_{OU} + T_{UI} + T_{II} + T_{UD} + T_t \tag{9}$$

where T_{OD}^{car} is the travel time from the point of origin to the destination by car; T_{OI} , T_{ID} are the travel times between the point of origin or destination, respectively, and the intercity public transit station; T_{OU} , T_{UD} are the time costs between the origin or destination, respectively, and the urban public transit station; T_{UI} is the travel time from the urban public transit station to the intercity public transit station by bus or metro; T_{II} is the travel time between two intercity public transit stations by coach or rail; and T_t is the transfer time at both intercity public transit stations.

The travel time from the origin to the destination by public transit is defined as the minimum time cost of all available public transit modes. This is calculated as

$$T_{ij} = \text{Min} \left(T_{ij}^{IPTW}, T_{ij}^{UIPTW} \right) \tag{10}$$

where T_{ij} is the shortest time spent from origin i to destination j by multimodal public transit and T_{ij}^{IPTW} and T_{ij}^{UIPTW} are the travel times of multimodal public transit without and with urban public transit, respectively.

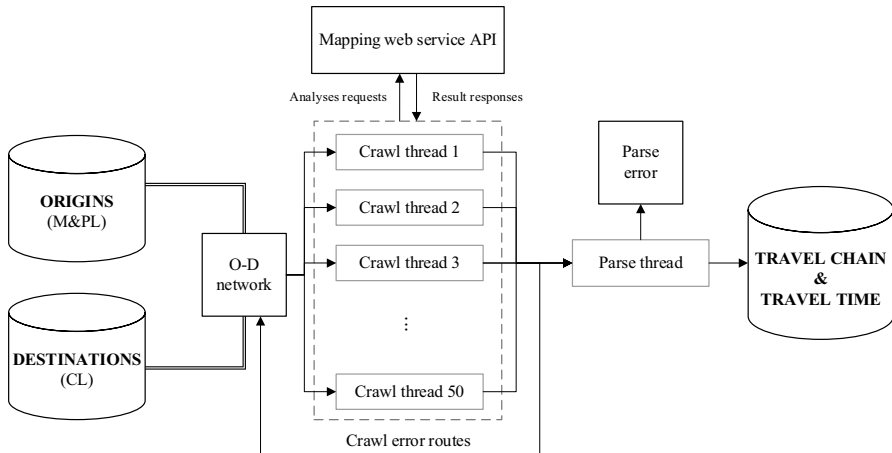


Fig. 3 Open-source massive path analysis (OMPA)

3.2.2 Open-source massive path analysis (OMPA)

In realistic journeys, travel time is underestimated because the time spent during transfers, waiting, traffic jams, and parking is ignored (Eluru et al. 2012). In addition, using a shortest path analysis based on the road network (Cao et al. 2013) or a layered cost distance (LCD) method based on cost grid units (Wang et al. 2016) is computationally intensive. Therefore, a method based on open-source massive path data for calculating the travel time was developed. Note that a travel time is obtained for each pair of cities, indicating the general time cost by different transportation modes. Traffic jam incidents and extra waiting time due to public transport schedule were not considered in driving and transit journey stages, respectively.

Because of large volume of data (M&PLs to CLs with a total of $337 \times 2848 = 959,776$ paths), it is of big challenge to obtain, organize and analyze the massive path data. An Internet mapping open platform was used to implement the OMPA method illustrated in Fig. 3. The OMPA method is based on the mapping web service application programming interface (API) provided by an Internet mapping service provider Baidu Map. The routes and travel times were acquired using a lightweight multithread program written in Python. The OMPA method comprises three basic steps: (1) set up an O-D network by connecting the origins (M&PLs) and destinations (CLs); (2) repeatedly invoke the mapping web service API by using a multithread (in this case 50 crawl threads, limited by the performance of processors, operation system, network status, etc.) to analyze each path in the O-D network; and (3) obtain the travel time and integrated travel chain by parsing the data acquired from the mapping web service API.

Limited by quotas of API, the crawler was run on several days. Since it was time-consuming due to the limitation of hardware and internet conditions, it also



Fig. 4 Paths from Beijing to all county-level divisions driven by car

ensures the departure time of our path data is all in working hours on workdays to reduce effects of traffic jam incidents.

The travel times and travel chains in the car driving and public transit modes were acquired for paths between all origins (M&PLs) and destinations (CLs). It is assumed that the OD travel time matrix is almost symmetrical. Thus, only one-way travel times from M&PLs to CLs were obtained presenting travel times between them. It is given in Fig. 4 a sample that the paths from Beijing to all CLs in the study area for the car driving mode.

4 Accessibility inequality in municipalities and prefecture-level (M&PL) divisions

4.1 The national-scale spatial distribution of accessibility

As presented in Sect. 3, Eqs. (1), (3), and (4) were used to calculate the accessibilities of 337 M&PLs according to the minimum time costs of all available transport modes (including car driving and public transit). Here, a higher β value in Eqs. (1) and (3) results in excessive reflection of adjacent destinations; therefore, we use 1 as the parameter. This value of β was also used by other scholars dealing with similar measures at a national scale (Gutiérrez 2001; Gu and Peng 2008; Cao et al. 2013; Kim and Sultana 2015). In Eq. (4), the time limit for returning on the same day is set to 3 h, considering the preference of passengers for an intercity round trip (Jiao et al. 2014; Wang et al. 2016).

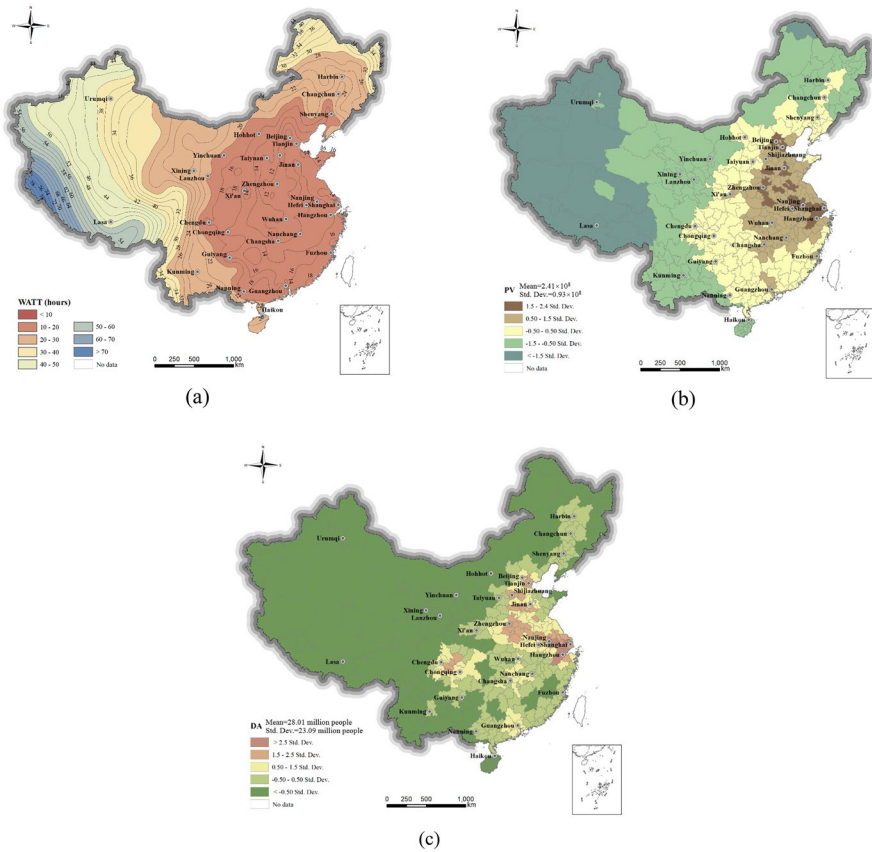


Fig. 5 Overall spatial distribution of accessibility for **a** weighted average travel time (WATT), **b** potential value (PV), and **c** daily accessibility (DA)

The WATT values were interpolated with spline, and results are plotted as contours in Fig. 5(a) to identify the overall spatial distribution pattern of accessibility. The city with the highest WATT value was Zhumadian, Henan Province, which is located in the geometric center of the Chinese transport network. The spatial distributions of accessibility for PV (Fig. 5b) and DA (Fig. 5c) suggest some similarities, but there remain considerable differences. M&PLs in the southern Jiangsu Province, northern Zhejiang Province, or Shanghai had both the highest PV scores (1.5–2.4 standard deviation) and highest DA scores (>2.5 standard deviation) because they benefited from superior traffic facilities and a high population density. Shanghai had the highest PV, and Zhenjiang was the M&PL with the highest DA. At the national scale, the PV and DA results suggested concentric circular patterns centered at the Yangtze River Delta, Beijing–Tianjin–Hebei, and Central Plain urban agglomerations. Comparing to WATT, PV and DA has stronger association with economic and population levels of M&PLs. Meanwhile,

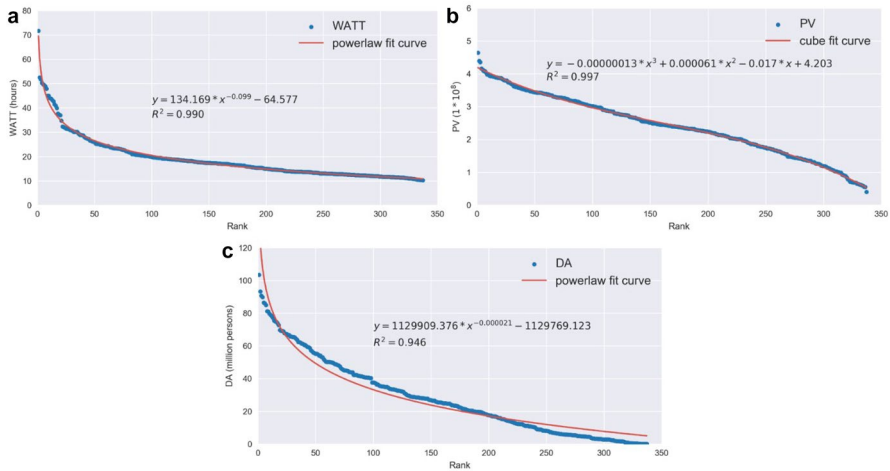


Fig. 6 Accessibility (y) vs. rank of cities (x): best fitting models **a** weighted average travel time (WATT), **b** potential value (PV), and **c** daily accessibility (DA)

M&PLs with centric location and ease transport system tend to have higher WATT values.

Overall, the results of the three indicators showed a decreasing trend from the eastern region via the midland to the northeastern and western region, which corresponded with the spatial pattern of the development level of the cities and transport infrastructure. Most M&PLs belonging to the Yangtze River Delta urban agglomeration had high accessibility (e.g., Shanghai, Suzhou, Hangzhou, Zhenjiang), and some M&PLs with high or extremely high accessibility were located in Henan and Hebei Provinces. M&PLs in Xinjiang, Tibet, Qinghai, Yunnan, and Hainan provinces had moderate or below-average accessibility according to the three indicators, among which Hainan is in the eastern region while the others are in the western region.

Note that travelling by car between Hainan and the mainland relies on ferries, and the travel time is affected by ferry schedules. Although travel times were underestimated due to ignoring waiting time for the ferry, it covers the duration of the ferry (approx. 1.5–2 hours). According to the inequality analysis, Hainan obviously has the worst accessibility in the eastern region, reflecting some barrier effects of the ferry.

4.2 Statistical characteristics of accessibility with the three indicators

By evaluating correlation coefficients between WATT, PV, and DA, PV had strong correlation with both WATT and DA. There was a strong positive relation between PV and DA with a correlation coefficient of 0.87. However, there were negative relations between WATT and PV and between WATT and DA with correlation coefficients of -0.85 and -0.61 , respectively. WATT indicates the

Table 1 Coefficients of variation (CV) of the weighted average travel time (WATT), potential value (PV), and daily accessibility (DA) indicators by regions (municipalities and prefecture-level (M&PL) divisions)

Indices	Statistical attributes	National level (337 M&PLs)	East (88 M&PLs)	Midland (82 M&PLs)	Northeast (36 M&PLs)	West (131 M&PLs)
WATT	Mean (hours)	19.02	14.91	12.49	23.85	24.54
	CV	0.46	0.20	0.10	0.21	0.43
	Weighted CV	0.32	0.19	0.26	0.06	0.16
PV	Mean (10^8)	2.41	3.06	3.18	1.79	1.66
	CV	0.38	0.22	0.14	0.27	0.37
	Weighted CV	0.96	0.40	0.29	0.11	1.19
DA	Mean (million people)	28.01	43.73	39.71	16.74	13.21
	CV	0.82	0.53	0.48	0.60	1.20
	Weighted CV	0.88	0.43	0.30	0.23	0.77

average travel time between cities, of which higher value (i.e., longer travel time) represents weaker accessibility. In contrast, a higher DA indicates more accessible opportunities.

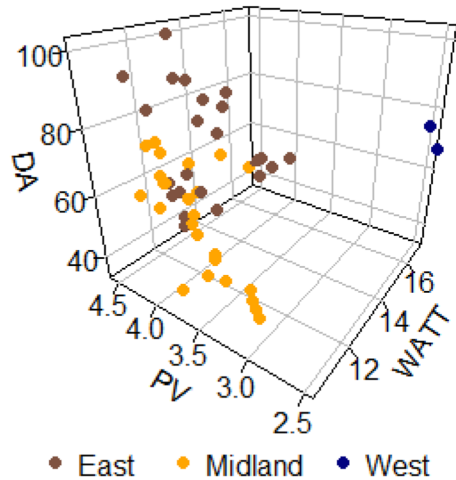
By evaluating the statistical distribution of three indicators, it is illustrated different characteristics of accessibility (Fig. 6). WATT and DA both conformed to the power-law distribution with R^2 scores of 0.990 and 0.946, respectively. PV, as the only indicator that considers declining effects of travel time, followed a cubic distribution with an R^2 score of 0.997. Higher WATT values indicate lower accessibility, while higher PV or DA values indicate higher accessibility. Thus, most M&PLs had better accessibility according to WATT, while most had weaker accessibility according to DA. Most M&PLs were moderately accessible according to PV. Only a small part of the M&PLs had economic activities with low or high potentials.

4.3 Inequality of accessibility

Table 1 lists the statistics of the accessibility indicators for every economic region. The midland had the highest average accessibility among all economic regions according to WATT (34.3% less than the national average) and PV (31.9% higher than the national average). The eastern region had the second-highest accessibility according to WATT (21.6% less than the national average) and PV (27.0% higher), and the highest accessibility according to DA (56.1% higher). M&PLs in the northeastern and western regions had below-average accessibility: WATT was 25.4% and 29.0% greater, respectively, than the national average; PV was 25.7% and 31.1% lower, respectively; and DA was 40.2% and 52.84% lower, respectively.

In terms of CV, the three indicators conformed to the following descending order: western region, northeastern region, eastern region, and midland. Similarly, western region has the highest weighted CV with PV and DA. But northeastern region has the lowest weighted CV. The midland has the highest weighted CV but the lowest

Fig. 7 Municipalities and prefecture-level (M&PL) divisions with accessibility ranked in top 30 for at least one indicator, weighted average travel time (WATT), potential value (PV), and daily accessibility (DA)



CV regarding WATT. There is great inequality of accessibility among regions: with regard to WATT, the CV ratios for the western region (0.43) was 4.30 times that for the midland (0.10); for PV, the CV ratios of the western region to midland is 2.64; and for DA, the CV ratios of the western region to midland is 2.50. In summary, there are significantly greater accessibility gaps within the western region, while M&PLs in the northeastern region had relatively equal accessibilities. There were 239 M&PLs with good WATT accessibility (<20 h), which accounted for 70.92% of all M&PLs: among which 84 M&PLs in the eastern region, 82 M&PLs in the midland, 12 in the northeastern region, and 61 in the western region. There were 82 M&PLs with moderate WATT accessibility, and most of them were located in the western region (54) or northeastern region (24). M&PLs in the eastern region with moderate WATT were Zhanjiang, Haikou, Danzhou, and Sanya, which are close to or located in the Hainan Province, the southernmost province of Mainland China. M&PLs with poor or very poor WATT are all located in the western region: particularly in the northwestern and western Xinjiang Province, and in most of the Tibet Province.

There were 89 M&PLs with good PV (0.5–1.5 standard deviation) that were in provinces with a high traffic network density, such as Hebei, Shandong, Henan, Jiangsu, Anhui, Hubei, Hunan, and Shanxi. Fuzhou, Guangzhou, Shenzhen, Foshan, and Zhongshan also had good PV because they benefited from their advanced economy. Most M&PLs, with a total of 113, have moderate PV (–0.5 to 0.5 standard deviation), accounting for 35.31% of the total M&PLs. M&PLs with poor (–1.5 to –0.5 standard deviation) or very poor (<–1.5 standard deviation) PV were mostly located in the northeastern and western regions except for Haikou, Danzhou, and Sanya, which were affected by geological barriers. Unlike PV, there were most M&PLs with very poor DA (<–0.5 standard deviation) among all DA levels, with a total of 130, followed by poor and moderate. There were only 28 M&PLs with good DA (1.5–2.5 standard deviation), all of which located around the urban

agglomerations. There were no M&PLs in the northeastern region with good or excellent PV and DA.

Ranking M&PLs by their accessibility with the three indicators, respectively, 12 M&PLs appeared in the top 30 for all three indicators: 4 are located in the eastern region, and 8 are in the midland. There are 49 M&PLs ranked in top 30 for at least one indicator (Fig. 7): 23 are located in the eastern region, 24 are located in the midland, and two are located in the western region. The eastern region and the midland have an obvious leading position in top accessibility cities in number. In Fig. 7, the two M&PLs in the western region (marked in blue) are dispersedly distributed from M&PLs in other regions-having the poorest WATT and PV accessibility. The gap has been widened by regional economy and the construction of transportation. Points representing M&PLs in the eastern region (in brown) and midland (in orange) are scattered in the fine-accessibility corner of the chart. Eastern M&PLs tend to have better PV and DA accessibility, while midland ones tend to be better in WATT. Notably, no M&PL belonging to the northeastern region appeared in the top 30 for any indicator. In the northeastern region, the M&PL with the highest WATT, PV, and DA accessibility only ranked at No. 177, No. 142, and No. 99, respectively, which was Huludao for WATT and Shenyang for both PV and DA).

5 Inequality in accessibility for different transport modes

5.1 Accessibility difference for various transportation modes

The measured accessibility was found to be closely related to the transport mode (Geurs and van Wee 2004; López et al. 2009; Wang et al. 2016). As discussed in Sect. 4.1, the minimum time costs of driving a car and public transit were used as the travel time to calculate the three accessibility indicators. However, accessibility is a complex concept, and different transportation modes for the calculation will lead to different results. Figure 8 presents the spatial distribution of WATT, PV, and DA in car driving and public transit modes. In car driving mode, the accessibility conformed to a concentric pattern. However, in the public transit mode, M&PLs with high accessibility were distributed along major railway lines, especially HSR corridors, and they extended to the northeast, southwest, and south.

Statistics are listed in Table 2. At the national level, moving from the car driving mode to the public transit mode reduced the accessibility: the mean WATT accessibility decreased from 19.75 h to 27.44 h, the mean PV (1×10^8) decreased from 2.26 to 1.74, and the mean DA (million persons) decreased from 25.59 to 12.88. The results for each economic region were consistent with the results at the national level. The largest accessibility gap between the two modes was in the western region, with differences of 44.63% for WATT and 44.15% for PV, while the eastern region showed the maximum DA gap of 52.54%. The CVs and weighted CVs of the three indicators were generally less in the car mode than in the transit mode, which indicates that the disparity in construction of public transport facilities is the major reason for the accessibility inequality. The western region has higher CVs for

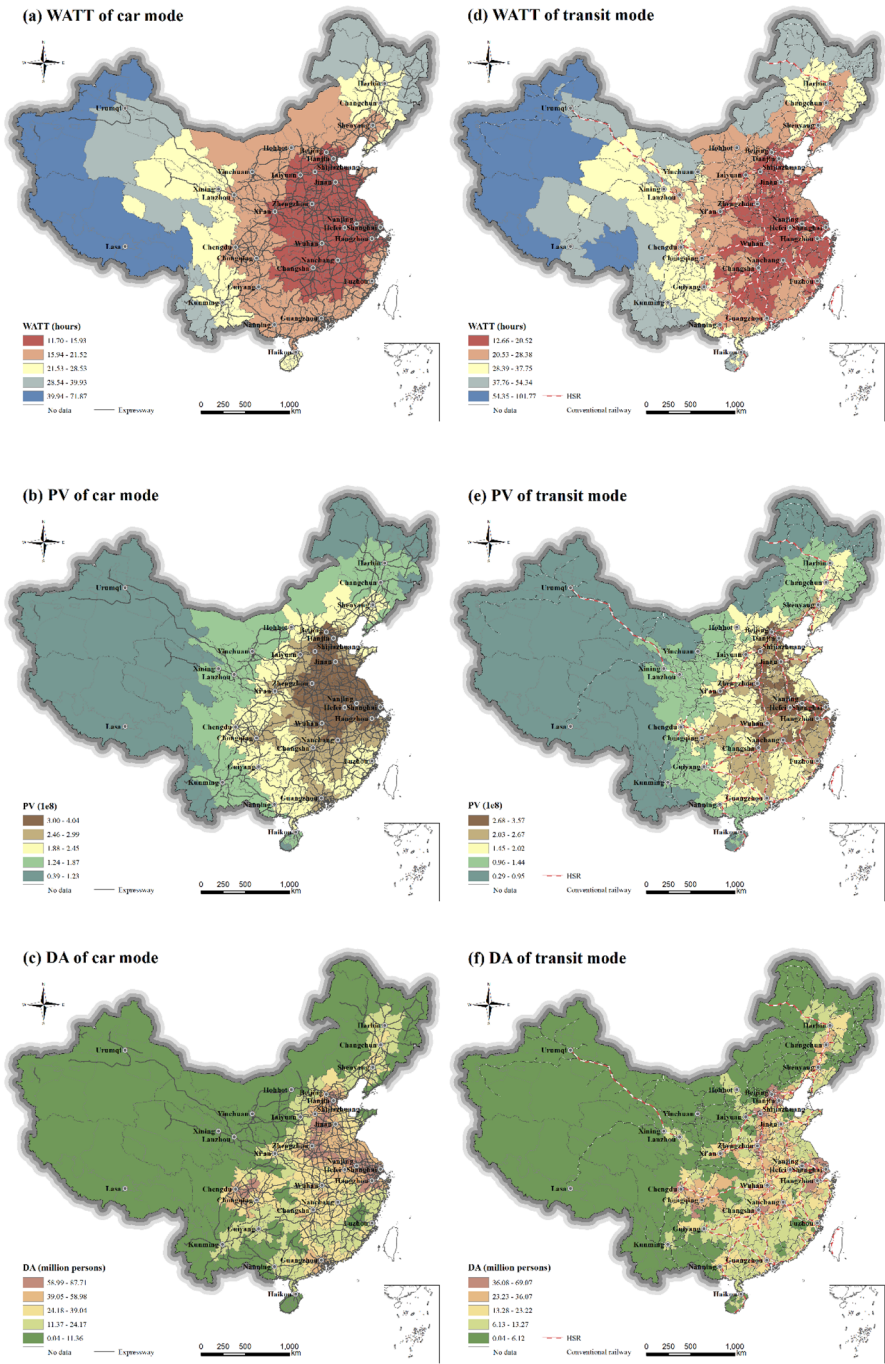


Fig. 8 Spatial distribution of accessibility in car driving and public transit modes with the transportation network (classified according to the natural break distribution; WATT stands for weighted average travel time, PV for potential value, and DA for daily accessibility)

Table 2 Coefficients of variation (CV) of the weighted average travel time (WATT), potential value (PV), and daily accessibility (DA) indicators for different transportation modes and municipalities and prefecture-level (M&PL) divisions

Indices	Transportation modes	Statistical attributes	National level (337 M&PLs)	East (88 M&PLs)	Midland (82 M&PLs)	Northeast (36 M&PLs)	West (131 M&PLs)
WATT	Car driving	Mean (hours)	19.75	15.92	13.16	25.21	24.96
		CV	0.44	0.18	0.08	0.18	0.42
	Public transit	Weighted CV	0.32	0.19	0.27	0.07	0.16
		Mean (hours)	27.44	21.12	18.37	32.04	36.1
PV	Car driving	CV	0.44	0.25	0.18	0.26	0.37
		Weighted CV	0.36	0.27	0.28	0.06	0.17
	Public transit	Mean (10^8)	2.26	2.83	2.97	1.63	1.61
		CV	0.36	0.2	0.12	0.23	0.36
DA	Car driving	Weighted CV	0.35	0.2	0.14	0.11	0.2
		Mean (10^8)	1.74	2.23	2.31	1.41	1.14
	Public transit	CV	0.43	0.28	0.23	0.35	0.39
		Weighted CV	0.47	0.27	0.18	0.1	0.28
DA	Car driving	Mean (million persons)	25.59	40.06	36.23	14.57	12.22
		CV	0.83	0.52	0.48	0.58	1.22
	Public transit	Weighted CV	0.88	0.43	0.3	0.22	0.77
		Mean (million persons)	12.88	19.01	17.3	9.82	6.83
DA	Public transit	CV	0.91	0.71	0.61	0.84	1.16
		Weighted CV	1.12	0.6	0.36	0.26	0.83

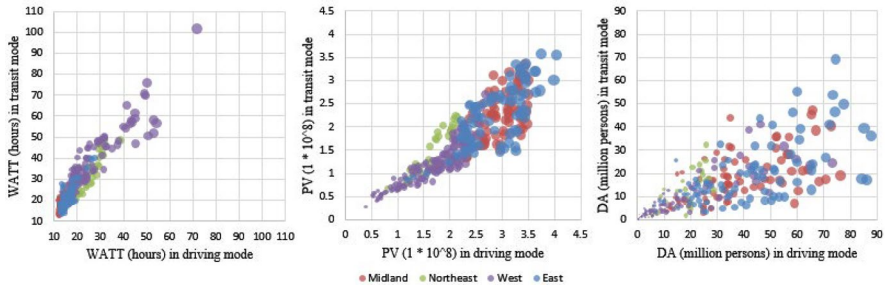


Fig. 9 Difference in accessibility between car driving and public transit modes according to the weighted average travel time (WATT), potential value (PV), and daily accessibility (DA) indicators of municipalities and prefecture-level (M&PL) divisions

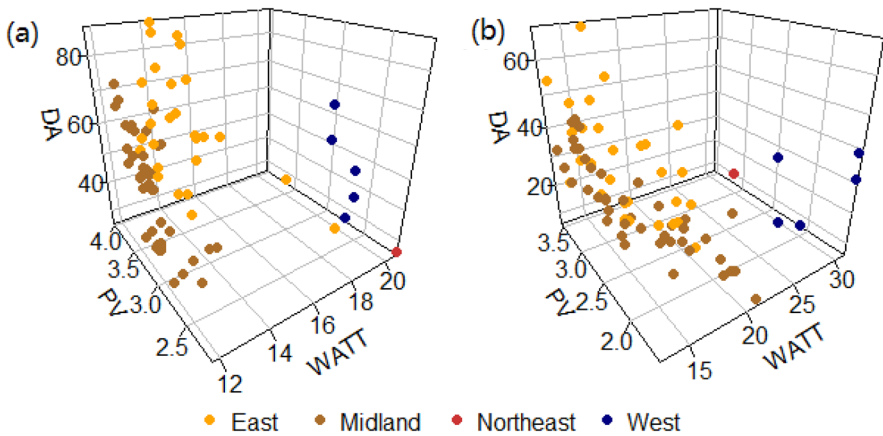


Fig. 10 Municipalities and prefecture-level (M&PL) divisions with accessibility ranked in top 30 for at least one indicator in **a** car driving mode and **b** public transit mode (WATT stands for weighted average travel time, PV for potential value, and DA for daily accessibility)

WATT and DA in car mode, but on the contrary for weighted CVs. For less populated regions, road network contributes more to the inequality than public transit network does.

Figure 9 shows differences in the accessibility for the M&PLs in the two transport modes. Most M&PLs set at the upper triangle for WATT and at the lower triangle for PV and DA, indicating they have better accessibility in driving mode than in public transit mode. In the car driving mode, the most accessible M&PLs were in provinces with dense expressway networks such as Beijing, Shandong, Shanxi, Hebei, Henan, Jiangsu, and Anhui. Compared to that in car driving mode, WATT accessibility significantly decreased in public transit mode in some regions including Shanxi, northern Jiangsu, and southern Jiangxi. However, M&PLs with high WATT accessibility extended to Guangzhou and Fuzhou along the Beijing–Jiulong and Ningbo–Beihai corridors. For PV and DA, M&PLs at the transit nodes of railway lines, especially

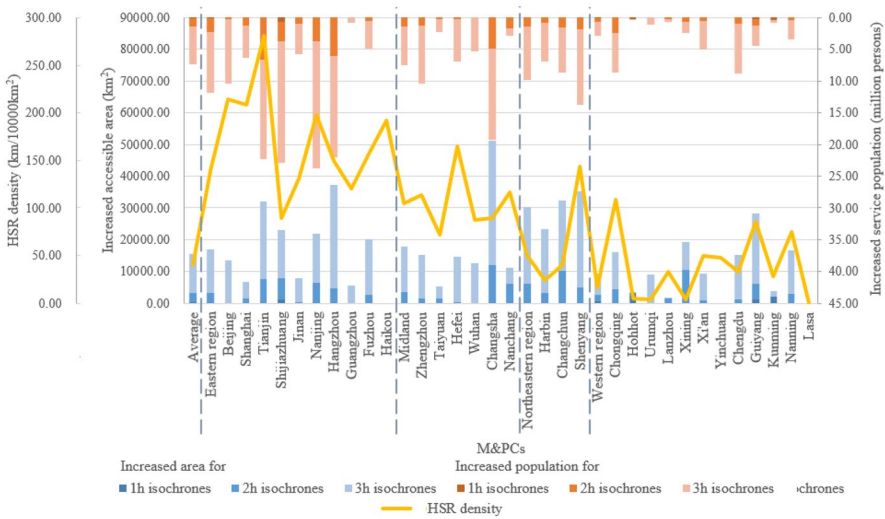


Fig. 11 High-speed rail (HSR) density, increased accessible area and service population with HSR for 1-h, 2-h, and 3-h isochrones

HSR (e.g., Beijing, Tianjin, Shijiazhuang, Zhengzhou, Nanjing, Wuhan, Shanghai, and Hangzhou), had the highest accessibility in the transit mode.

Ranking the M&PLs by their accessibility in the car driving mode and the public transit mode, respectively, there were 77 M&PLs ranked in top 30 in at least one mode for one or more indicators (Fig. 10). The top accessible M&PLs for the two transport modes shared some characteristics, but there were still a few variations. Eastern and midland M&PLs occupied most positions in the 77, and they had better accessibility. The M&PLs in the midland (brown points in Fig. 10) had their priority with WATT comparing to other regions. The best WATT accessible M&PLs in both transportation modes (Zhumadian and Zhengzhou) were in the midland. 12 M&PLs appeared in the top 30 accessible M&PLs according to WATT in both modes, all of which are located in the midland. Eastern M&PLs (orange points) also had relatively good WATT accessibility, and tended to have better DA than midland M&PLs. There were five top accessible M&PLs in western region (blue points), all of which are located in the Sichuan Province.

5.2 Influence of high-speed rail on daily accessibility

The HSR plays an important role in the Chinese transportation system because of its great economy, convenience, and eco-friendliness (Ryder 2012). To estimate the influence of HSR on daily accessibility, 31 municipalities and provincial capitals (M&PCs) were considered for two scenarios: (1) without and (2) with HSR. The OMPA method was used to obtain the minimum travel time from the origin to the destination for the two scenarios, by setting a parameter regarding intercity vehicle info when acquiring paths from the internet mapping service. Regions (CL) that conformed to the following conditions were selected to generate the isochrones: $T_1 <$

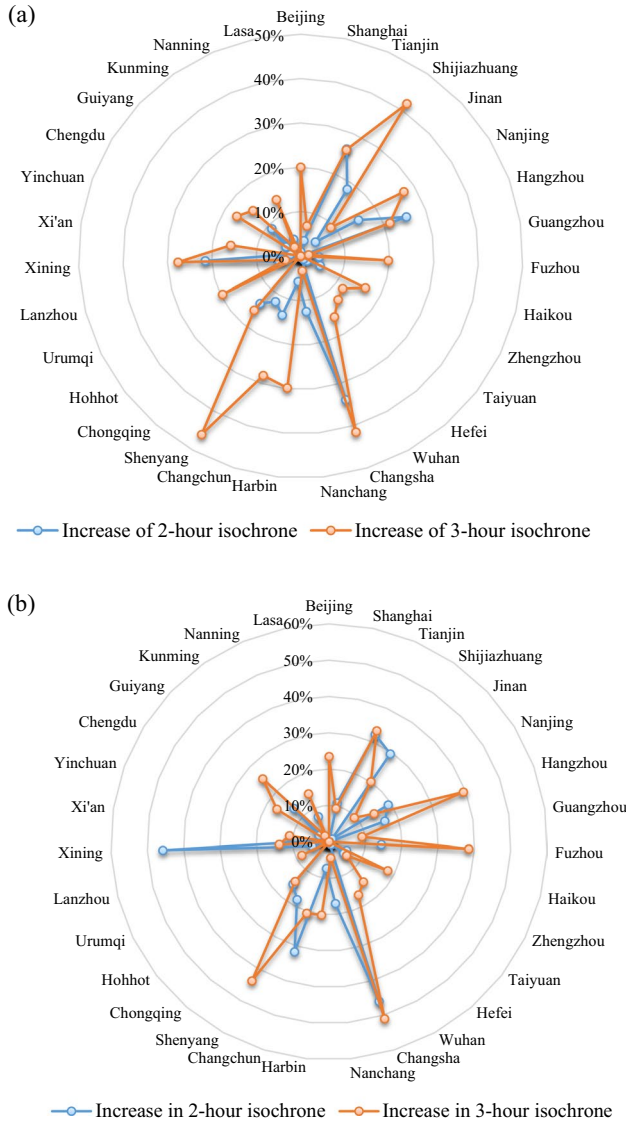


Fig. 12 Increases from scenario 1 to scenario 2 of the **a** accessible area and **b** service population

1 h, $T_2 \leq 2$ h, and $T_3 \leq 3$ h. For all isochrones, the accessible area and service population (i.e., DA) were determined based on the areas and populations of CLs in the isochrones.

Figure 11 displays how accessible area (blue bars at the bottom) and service population (orange bars on the top) increase for M&PCs with HSR, by 1-h, 2-h, and 3-h isochrones. Significantly, in the 1-h isochrones, the accessible area and service population without and with HSR were equal for most M&PCs except Shijiazhuang,

Hohhot, Guiyang, and Kunming. For the 2- and 3-h isochrones, the accessibility with HSR was better than those without in all M&PCs (Fig. 12). With the HSR network, the average accessible area increased from 31,444 to 34,522 km² (+ 11.20%) in the 2-h isochrones and from 79,308 to 91,404 km² (+ 15.62%) in the 3-h isochrones. The service population increased from 15.43 million to 16.76 million inhabitants (+ 7.86%) within the 2-h isochrones, and from 32.82 million to 38.81 million inhabitants (+ 15.47%) within the 3-h isochrones. Considering the difficulty of approaching the HSR station from the location of the government in most M&PCs, traveling to regions in 1-h isochrones costs more time than using traditional transport vehicles such as cars, buses, or subways (Jiao et al. 2014). HSR is not able to provide door-to-door service by itself. Thus, improving intracity transportation connections to HSR stations may efficiently extent the intercity accessibility with HSR, especially for short-distance travels.

By economic regions, the HSR had the greatest effect on the northeastern region with increases of 19.05% (2-h isochrones) and 28.18% (3-h isochrones) in the accessible area and 10.46% (2-h isochrones) and 34.65% (3-h isochrones) in the service population. Some of eastern and midland M&PCs also had great increases with HSR, but there was significant variation among M&PCs within these regions. For M&PCs, Changsha was benefited most from the HSR with increases of 46.00% (2-h isochrones) and 51.01% (3-h isochrones) in the accessible area and 33.92% (2-h isochrones) and 41.54% (3-h isochrones) in the service population.

HSR density (yellow line in Fig. 11) is the provincial HSR mileages per km² of each M&PC. In general, the eastern region and the midland have higher HSR density, and accordingly have more increase in accessible area and service population. For specific M&PC, its increase in accessibility caused by HSR is not directly related to its provincial HSR density. HSR mainly contributes to long-distance (2-h and 3-h isochrones) accessibility, thus increases in accessibility are more related to regional HSR system than local HSR system.

Figure 13 compares the daily accessible regions for M&PCs (e.g., Shanghai, Wuhan, Shenyang, and Chongqing as examples for every economic region) in scenarios 1 and 2. There was no appreciable change in the daily accessible region from scenario 1 to scenario 2 for the 1-h isochrone; however, significant changes were observed for the 2- and 3-h isochrones. The accessible region of scenario 2 was significantly spread out comparing to that of scenario 1. For Shanghai, the 3-h isochrones extended westward to Nanjing and Maanshan along the Beijing–Shanghai corridor. For Wuhan, the 2-h isochrone expanded northward to Xinyang and Zhumadian and southward to Yueyang along the Beijing–Jiulong corridor. For Shenyang, the accessible region extended southward and northward along the Harbin–Dalian corridor. For Chongqing, the accessible region extended eastward to Enshi and westward to Ziyang and Leshan along the Shanghai–Chengdu corridor. Notably, the daily accessible regions in scenario 2 were discontinuous and located at the HSR stations around the central M&PCs. In summary, compared with traditional transport facilities, HSR greatly increases the daily accessibility of M&PCs with an obvious corridor and station effects (Shaw et al. 2014).

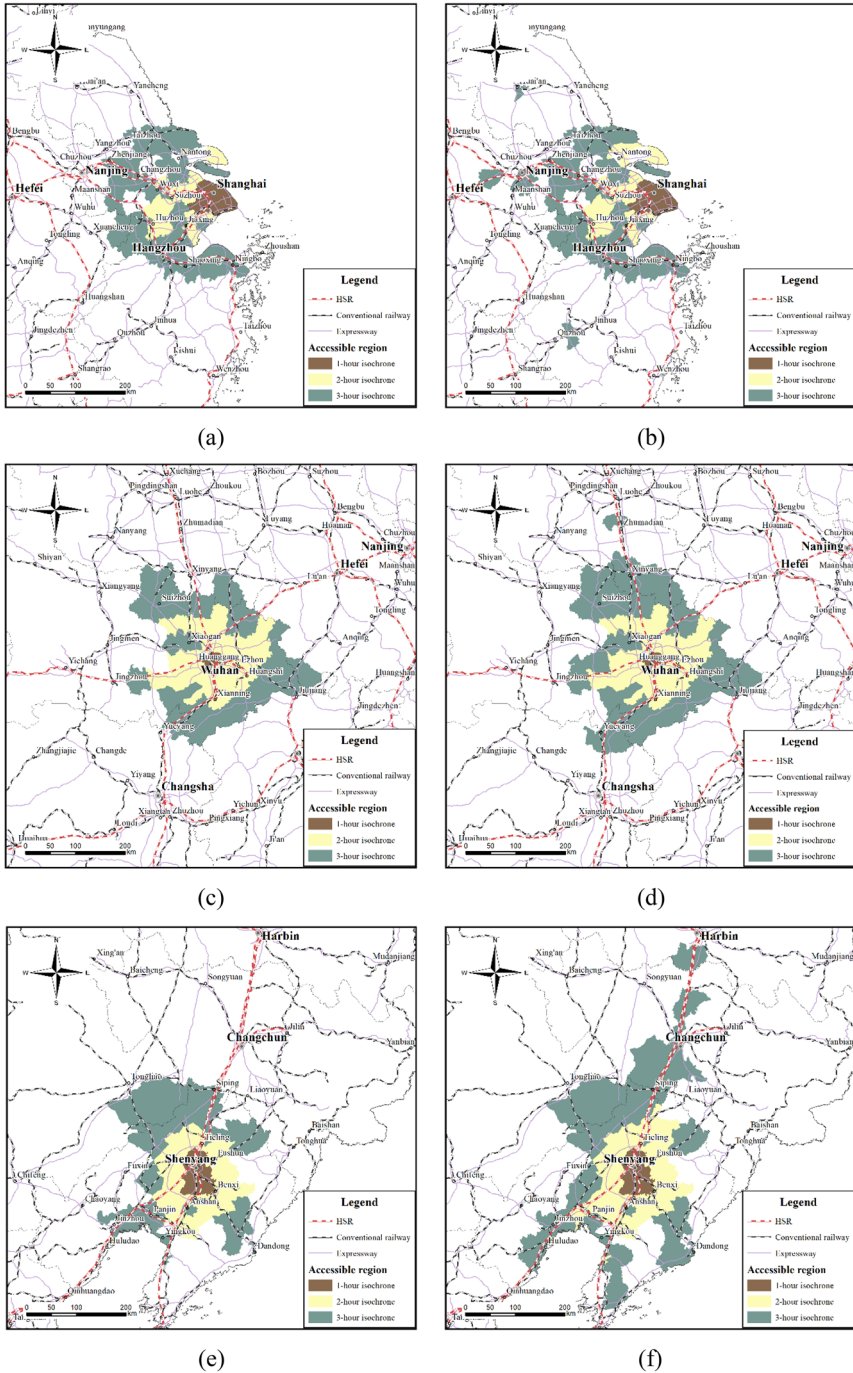


Fig. 13 Isochrones (1–3 h) in scenario 1 of a Shanghai, c Wuhan, e Shenyang, and g Chongqing and scenario 2 of b Shanghai, d Wuhan, f Shenyang, and h Chongqing

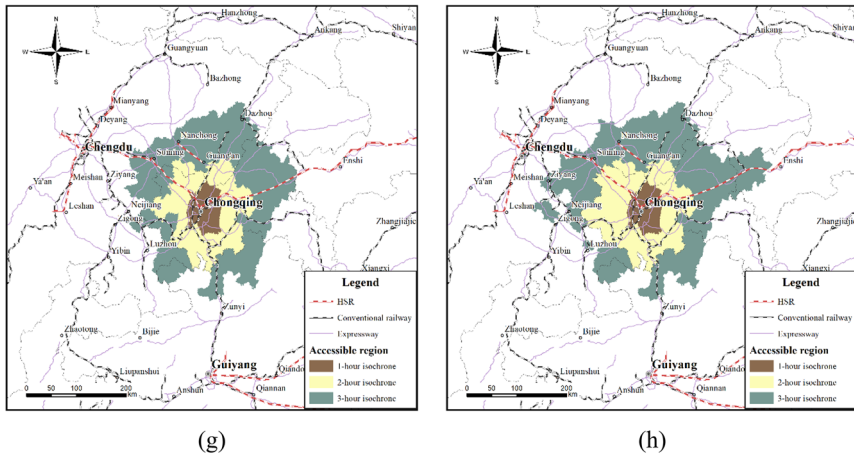


Fig. 13 (continued)

6 Discussion and conclusions

6.1 Discussion

Previous researches have similar findings with this paper. HSR contributes in improving accessibilities while enlarging regional inequalities (Jiao et al. 2014). Wang et al. (2016) concluded a 9.6% increasing in accessibility owing to HSR in Jiangsu Province, located in Eastern region. For shorter trips using urban transportation, the effect of the HSR network on the growth of daily accessibility is overestimated (Wang et al. 2014; Zhang et al. 2016) because of the high proportion of travel time required to access HSR. The change ratio of accessibility ranged from 4.69 to 50.46% as getting closer to HSR station (Jin et al. 2013).

The research also has some limitations that can be improved in future researches. More transportation modes can be considered for travel time, for instance, ferry, air traffic, etc. Air traffic significantly increases daily accessibility, especially that related to the service population (Chou 1993; Grubestic and Zook 2007; Yamaguchi 2007; Matisziw and Grubestic 2010; Sellner and Nagl 2010). Also, traffic jams and public transit schedules may influence accessibilities. Future research will consider more complete travel modes and more complex travel stages to evaluate accessibility. In addition, some important traffic factors and social factors will be quantified and evaluated for their impact on accessibility, such as the cost of traffic facilities, type of city, and per capita travel consumption. Moreover, this research uses administrative divisions and economic regions for analysis unit. It has provided credible conclusions and policy recommendations because accessibility is strongly related to socioeconomic factors. However, because of large volume of path data, what scale to choose is also limited by computational cost regarding hardware and internet conditions. Due to MAUP (Modifiable Areal Unit Problem), more division methods can

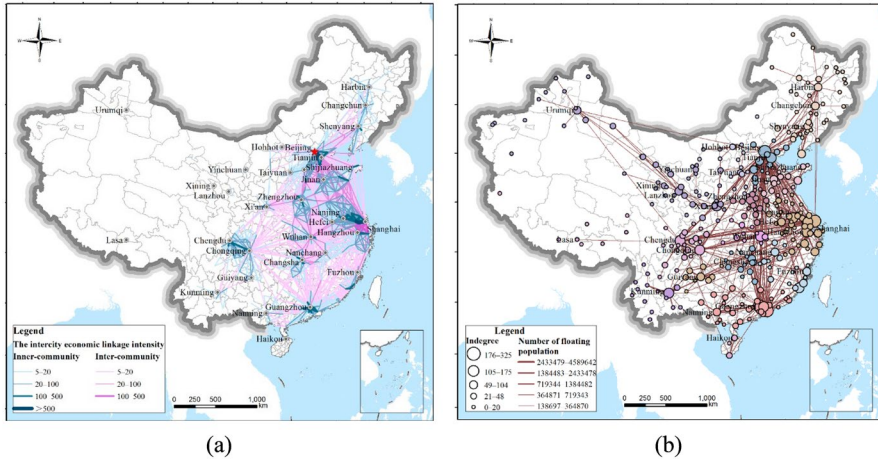


Fig. 14 Socioeconomic interaction networks built based on accessibility results: **a** economic linkage network and **b** population migrating network

be studied in future research to discuss about how areal units influence inequality results.

Accessibilities are often connected with spatial interactions on people migration, economic linkage, service sharing, etc. OMPA offers an opportunity to further study the correlation with accessibility and transport infrastructure, and to study its impact on socioeconomic interactions. Very first attempts were made by building a population migrating network and an economic linkage network based on accessibility results of this paper (Fig. 14). Results show interesting patterns correlating with both transport system and city functions. Considering this paper focuses on transportation inequalities, it will be a good prospect of urban and regional studies.

6.2 Conclusions

This study focused on spatial distribution and disparities in accessibility for economic regions and transportation modes within the Chinese mainland. We developed a method called OMPA, which collects data from web sites or travel planner to evaluate the patterns and disparities of accessibility. The proposed method demonstrates that it is possible to integrate intercity and intracity transport networks to precisely calculate the multimodal travel time, as well as evaluate the accessibility at a more detailed level and with various transport modes. Results of accessibility values can be updated, since the model input uses the crawling of open data sources with high relevance.

The major conclusions and policy recommendations are as follows:

- (1) Based on the travel time calculation integrating intercity and intracity transport networks, multiscale accessibility can reflect a more comprehensive realistic

distribution pattern of accessibility, making further analysis on the economic driver and inequalities more convincing.

- (2) Accessibility inequality was obvious between regions. In general, the spatial distribution of accessibility results for M&PLs on the Chinese mainland was similar to concentric circular patterns centered at provinces or municipalities at the center of the transport network. The eastern region and the midland have an obvious leading position. Benefited from the centric geographic location, WATT and PV indicated that the midland had the highest accessibility. DA indicated that M&PLs in the eastern region was the most accessible.
- (3) For transport modes, the inequality in the public transit mode was significantly greater than that in car driving mode because of various levels of transport infrastructure including public bus, metro, and railway networks, especially HSR. Further, the results indicated that improving the public transit facilities in the northeast region can dramatically promote the intracity accessibility of M&PLs there within a short time. Meanwhile, investing abundant resources in the transport infrastructure of the western region is more important for decreasing the intercity accessibility inequalities at the national scale in the long term.
- (4) HSR leads to a conspicuous spatiotemporal contraction and remarkable growth of daily accessibility (increased by 11.20% and 7.86% for the daily accessible area and service populations, respectively, in 2-h isochrones and 15.62% and 15.47%, respectively, in 3-h isochrones). The effect of HSR showed another inequality because the increases in accessibility were much larger in the north-eastern region than in other regions, especially than in the peripheral western region, where cities lack of direct connection with HSR networks. However, HSR has a more critical effect on daily accessibility for longer trip than for shorter trip, limited by intracity access to HSR stations.

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Declarations

Conflict of interest NonE.

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