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Study of the Impact of a High-Speed Railway Opening on China's Accessibility Pattern and Spatial Equality

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Abstract: China's high-speed rail was inaugurated in 2008; it has greatly improved accessibility, and reduced the time required to travel between cities, but at the same time, has caused an unfair distribution of accessibility levels. Therefore, this paper analyzes urban traffic roads and socio-economic statistics, using network analysis methods, accessibility coefficients of variation, and social demand indexes to explore the spatial and temporal characteristics of transport accessibility and spatial equity in China. By 2015, the national transport accessibility level will form a new pattern of “corridors” and “islands”, centered on high-speed rail lines and sites. Additionally, the opening of high-speed railways has improved, to a certain extent, the inter-regional accessibility balance, and increased accessibility from high-speed railway sites to non-site cities. Spatial equality was also analyzed using the accessibility coefficient and social demand index. In conclusion, studying accessibility and spatial equity plays an important role in the rational planning of urban land resources and transportation.

Keywords: accessibility; spatial equality; spatial-temporal differentiation; China

1. Introduction

A transportation network is formed by the daily commuting routes of a city's residents, as well as the methods of transporting goods, which include railways, highways, aviation, and waterways. The establishment of a good transportation network is thus important to the future development of a city [1–3]. Presently, high-speed railways have become an important part of the transportation infrastructure, forming a new trend for traveling between cities [4,5]. These high-speed railways not only improve the convenience of visiting cities, but also promote the economic development of en route cities, as well as cities not directly along the railway [6,7]. Additionally, high-speed railways have reshaped the collaborative relationships between a city and its surrounding areas, thus promoting regional economic integration [8,9]. Therefore, the study of transportation accessibility and spatial equality has become a hot topic in research in the fields of urban planning, social economics, and transportation [10].

“Accessibility” is an important measure of a transport network; it is used to measure the interaction potential between urban nodes in the transportation network [11–13]. This concept was first proposed by Hansen in the 1950s [14]. Presently, the research on urban transportation accessibility includes scale, transportation methods [15,16], and modeling [17]. It also focuses on the importance of

transportation networks in optimizing land use [18,19], patterns of tourism [20,21], housing prices [22], and the formation of a regional economic system [23]. Many studies have been primarily based on raster cost weighting and network analyses [24,25]. The weighted average travel time, economic potential, daily accessibility, and network efficiency were thus used to construct models to study accessibility [26,27]. For example, Gutiérrez used the potential accessibility index to assess the impact of high-speed railways on major cities along the route [28]. Jiang et al. adopted integrated network analysis and raster cost weighting to evaluate the impact of the Beijing–Shanghai high-speed railway on accessibility to central cities based on the weighted average travel time and potential value [29].

Transportation equity influences many social aspects, such as the time and cost spent on daily commutes, for educational purposes [30], and on public services [31–33]. Transportation accessibility is an important indicator for measuring inter-city visits, emphasizing residents' time spent on traveling, and their enthusiasm for participating in social activities. Accessibility has been gradually recognized as an indicator of transportation equity [34]. Presently, the evaluation of transportation equity is mostly focused on the needs of different social groups, population density, investment in transport facilities, and the strength of the external relationships of the city [35–37], and at the same time, uses the Lorenz curve and accessibility coefficient of variation (CV) to describe spatial inequality and accessibility [38,39]. The opening of high-speed railways has a non-uniform “corridor effect” on cities with or without stations along the route. Thus, this phenomenon may lead to some differences in the spatial distribution of accessibility. For example, Monzón et al. and López et al. used the CV of economic potential to study the impact of the Spanish high-speed railway expansion on city efficiency and equity [40,41]. Kim and Sultana used the potential accessibility and weighted average travel time to determine the effect of high-speed railways on regional equity in South Korea [42]. With the rapid development of society and improvements in living standards, the social demand indicator of each city has become different. Social indicators depend, to some extent, on the economy, population, and other indicators [43,44]. Therefore, the social indicator and the spatial distribution of accessibility illustrate the spatial equality problem [45,46]. To accurately reflect the problem of spatial equality, a selection of indicators and evaluation methods has been studied by many researchers.

Currently, many researchers use the spatial distribution of accessibility to illustrate China's spatial equality, but they seldom consider the social needs of cities. Considering the large difference in social needs of different cities, this study explores the impact of accessibility and spatial equality after the opening of the high-speed rail. It will then provide a reference for road planners and policy makers to narrow the gap in accessibility between cities.

2. Methodology

This section describes the calculation methods of accessibility and equality, in order to reflect spatial equality by calculating the accessibility and social demand indicator. The first part describes the accessibility and index selection. The second part describes the CA and social demand index and establishes a social demand indicator system.

2.1. Accessibility Measures

Accessibility concepts and measurement are very important for urban transportation researchers and planners. There are many ways to measure accessibility, such as the distance method, topology method, cumulative chance method, and the gravity model [47,48]. The measures of accessibility are mostly concentrated on the shortest time between cities, the cost and the comprehensive evaluation of the transport network [49]. However, many researchers measured accessibility using a single angle previously, often neglecting the cost of urban transportation trips, socio-economic, and demographic factors. Therefore, this study selects two indicators of generalized weighted average travel time and economic potential to describe accessibility spatial characteristics.

2.1.1. Generalized Weighted Travel Time

The generalized weighted travel time (GAT) represents integrated time and cost to measure accessibility, where the lower the value, the better the accessibility. Therefore, it is of great importance as a measure of transportation accessibility [50].

$$a_{ij} = \min \left[\frac{M_j \times T_{ij}}{\sum_{j=1}^n M_j} + \frac{F_{ij}/TV_j}{\sum_{j=1}^n (1/TV_j)} \right] \quad (1)$$

$$TV_j = GDP_j / (P_j \times WH) \quad (2)$$

$$A_i = \sum_j a_{ij} \quad (3)$$

In the above equations, a_{ij} represents inter-city accessibility. F_{ij} represents the lowest travel cost. M_j represents the total population of city j . T_{ij} represents the shortest travel time. TV_j represents the generalized travel time of a city. Here, a_{ij} , F_{ij} , and T_{ij} are obtained using the ArcGIS Network Analysis Module. TV_j represents the contribution of the gross domestic product (GDP) per capita per hour in city j . P_j and GDP_j represent the population and GDP of the destination city, respectively. WH represents the standard working hours per year (2000 h) in China. A_i represents the GAT of city i .

2.1.2. Economic Potential Accessibility Index

The potential accessibility index (PA) represents the total amount of economic activities in cities and can reflect the strength of interaction among cities and the diffusion capacity [51].

$$PA_i = \sum_j \frac{M_j}{T_{ij}} \quad (4)$$

In the above, PA_i denotes the economic potential of city i ; the greater the value, the better the accessibility, and vice versa. T_{ij} represents the minimum time required to travel from node city i to city j .

2.2. Spatial Equality

The research on transportation equity is mostly concentrated on land use, population distribution, economic level, and public service, but its concept is still vague, with no clear standard for its definition [52–54]. Transportation equity can be generalized to both horizontal and vertical aspects [55]. Horizontal equity refers to the equal allocation of resources for all members of society under certain conditions. It mainly analyzes the spatial distribution of accessibility in space, and does not take into account the social needs of different regions [56]. Vertical equity needs to take into account the income of different residents, residents' needs, age groups, and so on, followed by an analysis of the issue of spatial equality [57,58].

2.2.1. Coefficient of Variation

The degree of regional accessibility is measured by CV, which has been widely used in previous studies too [59,60]. This study applies CV as an evaluation indicator of transportation equity:

$$CV = \frac{\sigma^P}{\frac{\sum A_i \times M_i}{\sum M_i}} \quad (5)$$

where CV represents the accessibility CV , σ^P represents the standard deviation of accessibility, and A_i represents the accessibility value, which is the GAT or PA .

2.2.2. Social Demand Indicator System

Since the 1980s, people have gradually used social demand indicators to reflect the issue of spatial equality, and combined the social needs and the spatial distribution characteristics of accessibility to illustrate transportation equity. Social indicators have been widely used to reflect the issue of spatial equality [61,62]. For example, Hao et al. analyzed the demand of urban transportation in China using indicators like low-income groups, disabled population, and aging population [63]. Xia et al. analyzed the Perth transportation equity problem by incorporating no-car groups into social demand indicators [64]. Therefore, how to select social demand indicators and build a comprehensive evaluation index system has become an important part of evaluating equity issues.

The construction of the social demand evaluation system is a prerequisite for the study of transportation equity. This study selects 13 social demand indicators from the three aspects of population, economy, and society to build a social demand indicator system (Table 1). Finally, the Global Principal Component Analysis (GPCA) is used to calculate the social demand index of each city [43,65].

Table 1. Social demand indicator system.

| Objective | Criteria | Indicator | Description |
|--------------------------|------------|---|---|
| Social demand indicators | Population | X1 Population density (people/km ²) | Proportion of population accounting for secondary and tertiary industries |
| | | X2 Population different age groups | Population age (<15 years old, 15–64 years old, >64 years old) |
| | | X3 Floating population | Person whose residence is inconsistent with the residence registration |
| | | X4 Registered unemployed population in cities and towns | |
| | | X5 Student population | Ordinary high school students, ordinary middle school students, primary school students |
| | Economy | X6 Regional GDP per capita (10,000 yuan/capita) | Total urban GDP/Total population |
| | | X7% of secondary, tertiary industries (%) | Secondary, tertiary industry GDP/Total GDP |
| | | X8 Saving per capita (%) | The total sales of consumer goods/Total population |
| | Society | X9 Investment in fixed assets accounted for GDP (%) | Investment in fixed assets/total GDP |
| | | X10 Proportion of non-agricultural workforce | Non-agricultural workforce/Total workforce |
| | | X11 Proportion of education and science account for local finance expenditure (%) | Expenditure on education and science/Local fiscal expenditure |
| | | X12 Bus per 10,000 people (bus/10,000 people) | Number of bus/Total population |
| | | X13 Number of medical institutions (institution/10,000) | Number of hospital beds/Total population |

3. Study Area and Data

3.1. Study Area

In China, as urbanization progresses, inter-regional economies become more closely linked, and the construction of integrated urban transportation infrastructure becomes more prominent. Cities with a high population density in China are mostly concentrated in the eastern region, mainly in the plains and hills, and belong to the monsoon season. High-speed rail is mostly distributed in the eastern and central regions. In July 2016, the National Development and Reform Commission approved the “The mid- to long-term railway network development plan”, which proposed two networks—high-speed and ordinary railways. By the end of 2015, China’s railway operation had reached 121,000 km, wherein the high-speed railway covered 19,000 km. This study explores the spatial and temporal characteristics of transportation accessibility and spatial equality before and after the opening of China’s high-speed rail (Figure 1).

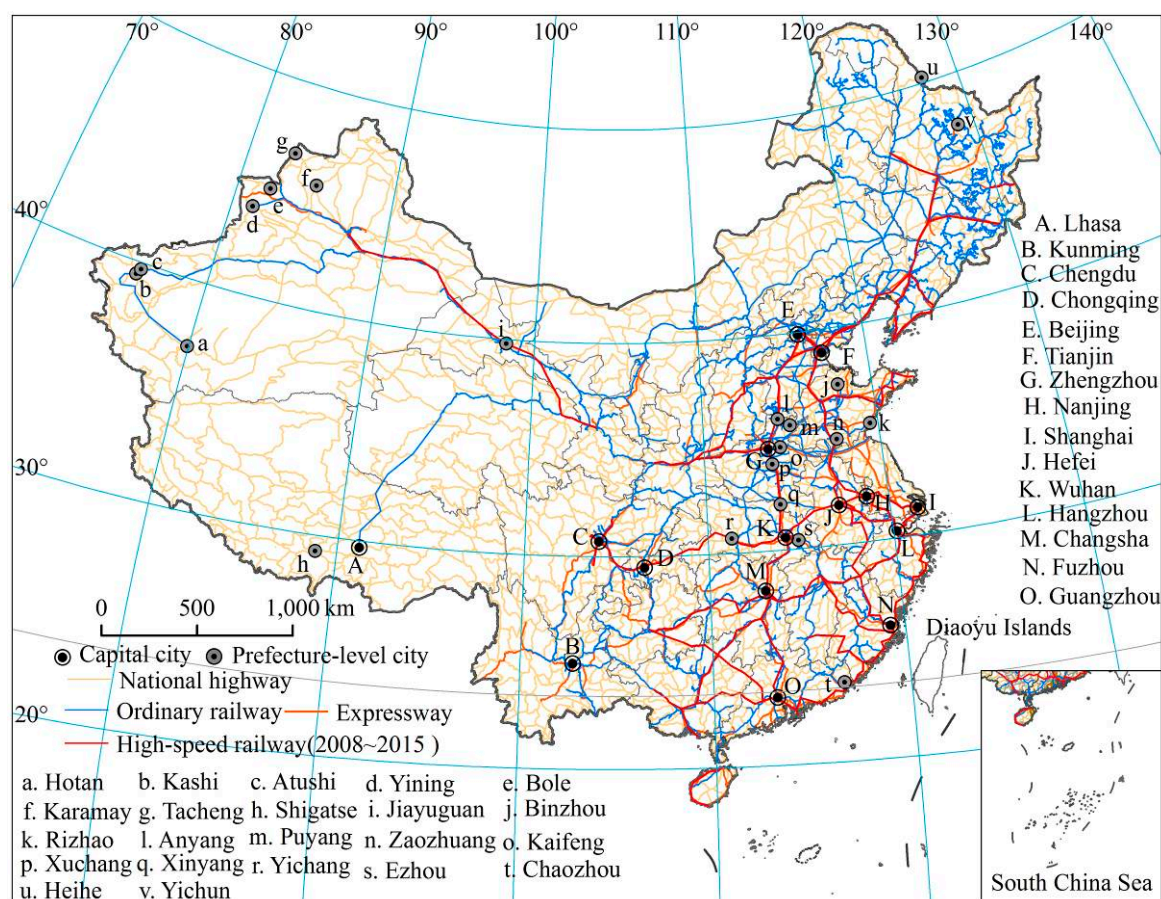


Figure 1. Transportation network in China from 2008 to 2015.

3.2. Data Sources and Processing

This study is based on two periods of national traffic road data (1: 250,000), high-speed railway data, basic attributes, and socio-economic data (Table 2). The high-speed railway was first introduced in China in 2008, and is used as the starting point to evaluate transportation accessibility and differences in spatial-temporal equality. In accordance with the “People’s Republic of China highway engineering technical standards” and “The mid- to long-term development plan of China’s railway (2008–2020),” transportation networks are assigned the following speed definitions: high-speed railway (300 km/h), bullet train (250, 200 km/h), ordinary train (90 km/h), express highway (100 km/h), national highway (80 km/h), provincial highway (60 km/h), and country road (40 km/h). “China economic and social development statistical database” and related research articles are used to calculate travel cost for high-speed railway (1.75 Yuan/min), bullet train (0.75 Yuan/min), express highway/national highway/provincial highway/country road (0.1 Yuan/min), and ordinary railway (0.22 Yuan/min) [66].

Table 2. Data sources and description.

| Data Sources | Description |
|--|--|
| National Geographic Information Bureau | Ordinary railway, express highway/national highway/provincial highway/country road data |
| “The mid to long-term railway network development plan” (2030) | 2008–2015, Data from cities with high-speed railway and Railway stations by geographical registration http://crh.gaotie.cn/ |
| “The mid to long term development plan of China’s railway” (2008–2020) | http://www.360doc.com/content/11/0218/23/4665399_94209414.shtml |
| “China Statistical Yearbook” (2008 and 2016) | Social indicator based on different age groups and socio-economic factors. |

4. Results and Analysis

4.1. Temporal-Spatial Variation of Accessibility

4.1.1. Generalized Weighted Travel Time

The temporal and spatial distribution of time-space distribution in China (Figure 2) was calculated using GAT reachability (Equations (1)–(3)).

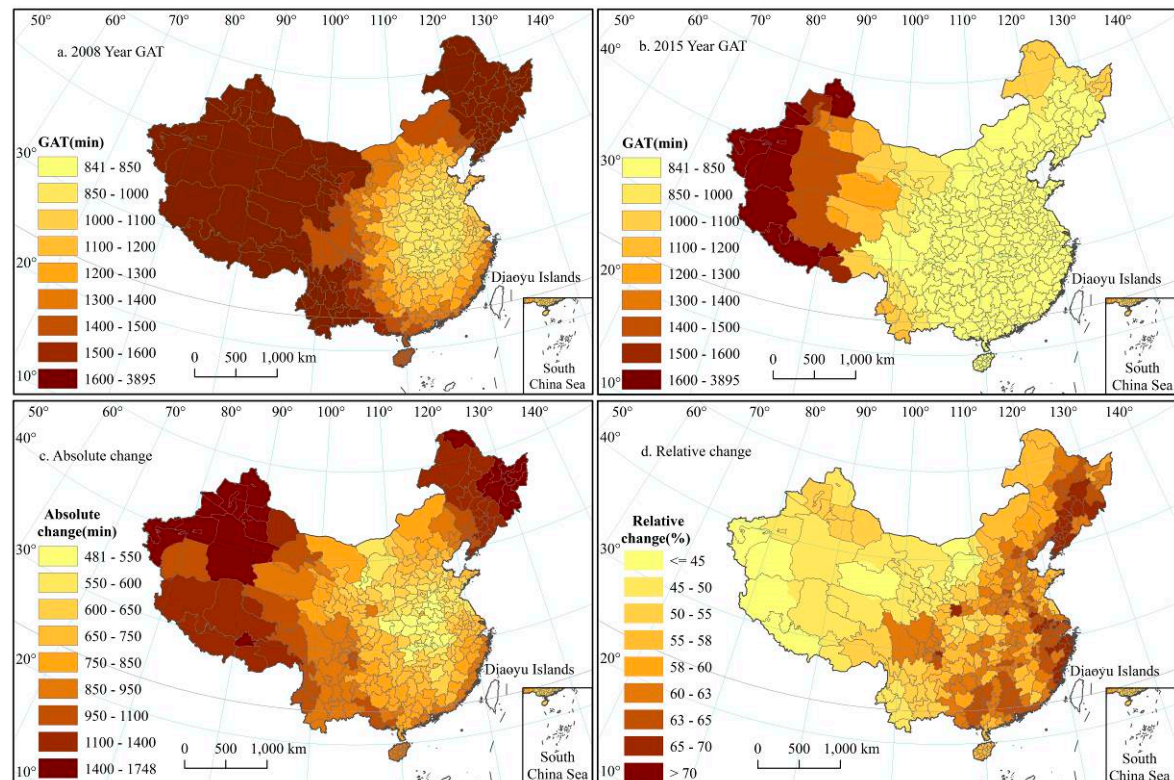


Figure 2. GAT spatial distribution.

GAT spatial distribution (Figure 2) shows that, before 2008, GAT formed a spatial pattern with Henan and Hubei as low-value cores with gradual expansion in the surrounding areas. The low-value core areas include Xinyang, Kaifeng, Xuchang, Wuhan, and Ezhou, with an average value of 872.91 min. High-value areas are concentrated in western China, such as in Atushi, Kashgar, and Hotan cites, which have poor transportation networks because of the climate, population density, economic factors, and political elements.

From 2008 to 2015, with the introduction of high-speed railways, the national GAT showed an overall reduction of 59.53%. This formed a high accessibility pattern along the high-speed railway, with destination cities as core nodes. In terms of magnitude of change, the absolute change in the northwestern and northeastern cities, such as Lhasa, Kashi, Jixi, or Yichun, is the most evident. In terms of relative change, central and eastern regions, such as Guangzhou, Changsha, Hefei, Fuzhou, Shanghai, Hangzhou, Nanjing, Beijing, or Chongqing, have exceeded the 60% mark because of the impact of multiple high-speed railways, including the Beijing–Shanghai, Beijing–Guangzhou, Hangzhou–Fuzhou–Shenzhen, Shanghai–Kunming, and Shanghai–Yichang–Chengdu routes. This result further shows that high-speed trains reduced traveling time between regions, thereby strengthening the socio-economic ties of remote areas with eastern and central regions.

4.1.2. Economic Potential

Using the PA approach (Equation (4)), the temporal and spatial distribution of China's PA is computed (Figure 3).

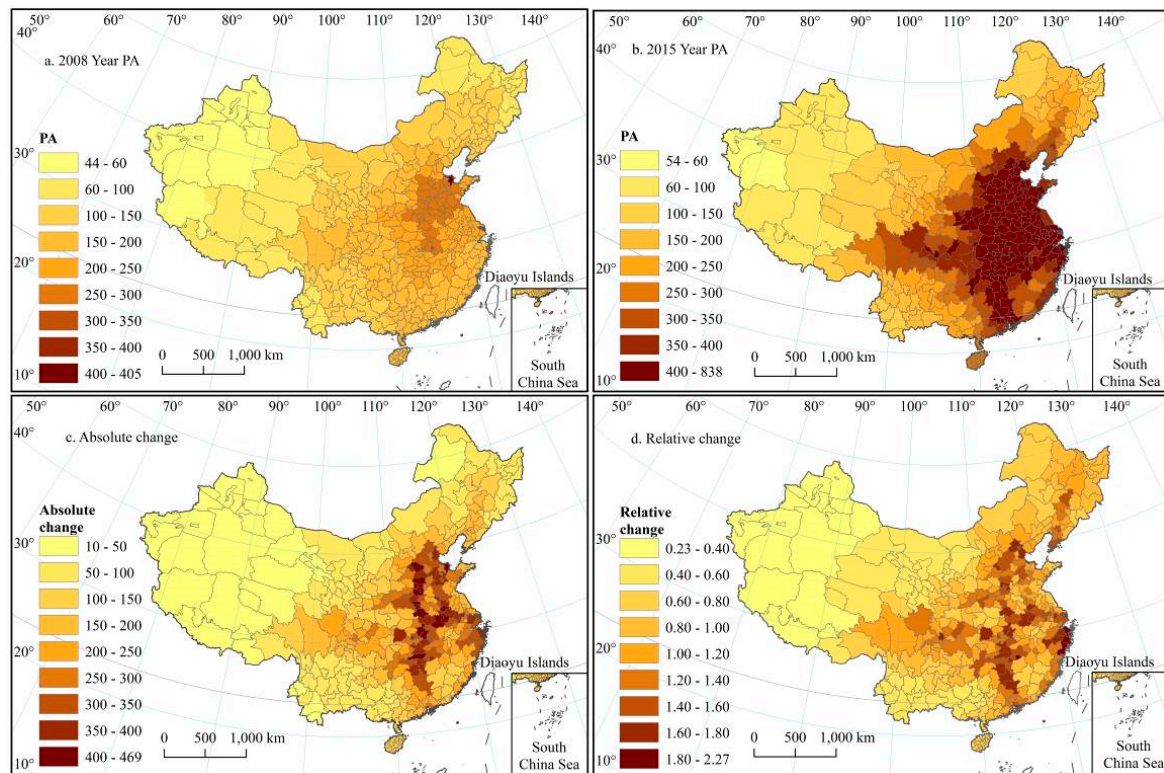


Figure 3. Spatial distribution map of economic potential.

The economic potential indicates that, before 2008, cities for which the PA exceeded 300 were mostly located in the central eastern region of Henan Province (Figure 3). Areas with economic potentials below 60 were mostly concentrated in western Xinjiang and remote areas in Tibet. Therefore, this distribution forms a pattern of “concentric circles” with the mid-eastern region as high-economic potential cores; this region’s high-value core areas include Ezhou, Xuchang, and Kaifeng, while Atushi, Lhasa, Bole, and Yining are the western low economic potential cities.

From 2008 to 2015, the economic potential of China increased by 118.61%. Economic potential is higher in cities along the high-speed railway and those with stations, such as Kaifeng, Anyang, Zhengzhou, and Hefei, which have economic potentials above 700. Low economic potential areas are still concentrated in the western region’s remote areas of Yunnan, Heilongjiang, and Inner Mongolia, with an average increase in economic potential of 28.17%. The results indicate that high-speed railways have strengthened the economic diffusion capacity and connection between cities, thereby promoting the development of economic potential in remote areas.

4.2. Spatial-Temporal Differentiation of Equality

4.2.1. Coefficient of Variation

Accessibility CV is used to evaluate transportation equity (Equation (5)). Table 3 presents the following two aspects. First, all sample cities’ accessibility CV increased by 0.34 and 0.16, showing that, over eight years, the balance of accessibility difference increased. At the same time, the difference in economic potential balance is lower than the GAT. Second, in cities with and without high-speed train stations, GAT (CV) increased by 0.11 and 0.29, respectively. The economic potential CV increased

by -0.02 and 0.18 , respectively, which indicates that the balanced difference of travel time in cities with high-speed train stations is smaller than that in non-destination cities. Moreover, the high-speed railway reduced the balanced difference of economic potential in cities with train stations and promoted the economic potential value for non-destination cities.

Table 3. Accessibility CV.

| Category | GAT | | | | | PA | | | | |
|-------------------------|---------|-------------------|--------|-------------------|-----------|--------|------------------|--------|------------------|-----------|
| | 2008 | CV _{GAT} | 2015 | CV _{GAT} | CV Change | 2008 | CV _{PA} | 2015 | CV _{PA} | CV Change |
| All cities | 1368.76 | 0.422 | 553.92 | 0.566 | 0.34 | 180.94 | 0.312 | 395.56 | 0.363 | 0.16 |
| Cities with stations | 1283.55 | 0.291 | 467.94 | 0.322 | 0.11 | 194.80 | 0.276 | 453.44 | 0.270 | -0.02 |
| Cities without stations | 1402.17 | 0.455 | 587.63 | 0.585 | 0.29 | 177.03 | 0.330 | 382.15 | 0.389 | 0.18 |

4.2.2. Social Demand Indicator

This section is mainly based on the constructed social demand index (Table 1), and uses the GCPA to determine the contribution rate of the main factors and the comprehensive score. As shown in Table 4, three principal component factors were extracted, with a cumulative variance contribution rate of 80.722% , indicating they all contained basic information. To discuss the spatial distribution of the social demand indicator, this study divides the latter into certain intervals (Figure 4). Among them, the lighter color represents lower urban social demand indexes, and the darker color represents higher social indexes, thus requiring higher accessibility.

Table 4. Principal component eigenvalue and variance contribution rate.

| Principal Component | Eigenvalue | Variance Contribution Rate % | Accumulative Variance Contribution Rate |
|---------------------|------------|------------------------------|---|
| 1 | 7.492 | 49.945 | 49.945 |
| 2 | 3.476 | 23.173 | 73.118 |
| 3 | 1.141 | 7.604 | 80.722 |

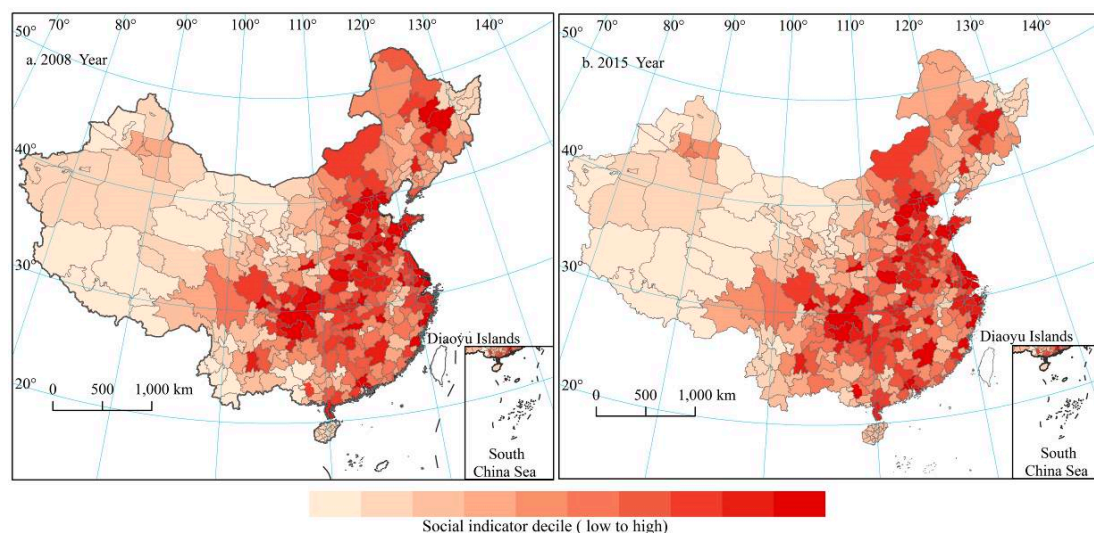


Figure 4. Social indicator deciles, 2008 and 2015.

The spatial distribution of the social demand indicator (Figure 4) shows that, in 2008, the cities with high social demand index included Beijing, Wuhan, Tianjin, and Shanghai, with a demand index above 10. This region has been influenced by many factors, such as history, culture, policy, and economy. As such, the comprehensive development level of the cities is relatively high. Moreover, in Xinjiang's Tacheng City, Karamay City, Gansu's Jiayuguan, Tibet's Lhasa, and other cities, the social demand index is low. As of 2015, cities with a high urban social demand indicator in China are still

concentrated in the eastern and central regions—mostly high-speed rail sites—and are located at the intersection of high-speed rail lines, such as Beijing, Tianjin, Chengdu, and Wuhan. Overall, from 2008 to 2015, the national urban social demand index increased by an average of 0.12, with absolute changes being registered in the largest cities, such as Shanghai, Hefei, and Tianjin, and relatively large changes in cities like Chaozhou, Heihe, and Yichang.

4.2.3. Trends by Social Indicator Decile

To further analyze the relationship between urban transportation accessibility and social demand, this study considers the relationship between its standardized values, as shown in Table 5. Over the past eight years, the gap between the social demand indicator of each city increased; the range of generalized weighted average travel time and potential value increased by 0.63 and -1.18 , respectively; and the median by, -0.14 and 0.12 , respectively. To a certain extent, this reflects the high-speed railway increasing generalized weighted average travel time differences between cities, thus narrowing potential accessibility differences.

Table 5. Standardized accessibility index and social indicator.

| | Year | Maximum | Minimum | Range | Median |
|------------------|------|---------|---------|-------|---------|
| Social indicator | 2008 | 13.92 | -5.56 | 19.48 | -0.63 |
| | 2015 | 17.10 | -5.82 | 22.92 | -0.81 |
| GAT | 2008 | 4.47 | -1.08 | 5.55 | -0.20 |
| | 2015 | 5.27 | -0.91 | 6.18 | -0.34 |
| PA | 2008 | 3.78 | -2.08 | 5.86 | -0.08 |
| | 2015 | 2.83 | -1.85 | 4.68 | 0.04 |

The distribution of accessibility is analyzed based on the decile of the social demand index of cities across the country, in 2008 and 2015, as shown in Figure 5. Among them, the first decile of urban groups indicates the lowest social needs. For the first and third deciles, urban groups have lower social demand indices, and thus, an overall higher average weighted average travel time, which indicates lower accessibility. However, during the past eight years, the generalized weighted accessibility of the first and third decile city averages increased by 0.38 and 0.09, while the first decile range increased by 1.39, indicating that high-speed rail widened the city and overall national accessibility levels (e.g., the cities of Karamay, Jiayuguan, Lhasa, and Shigatse City).

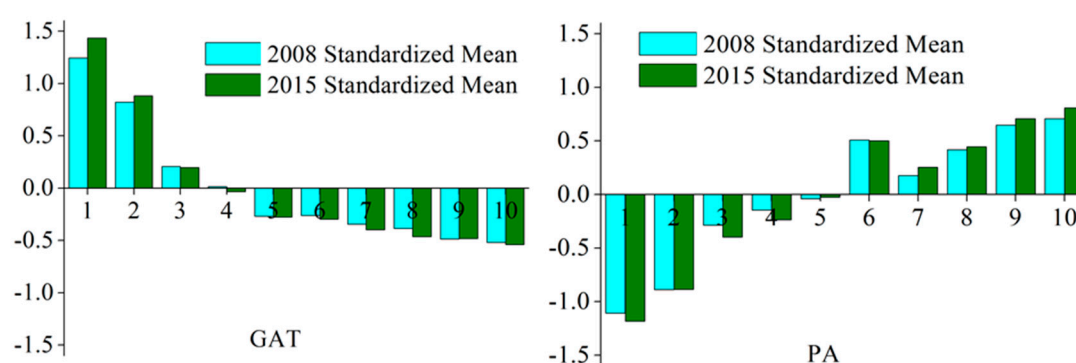


Figure 5. Accessibility by social needs indicator deciles.

By analyzing the potential accessibility of different city deciles over these eight years, the average transportation accessibility of potentials, in addition to the third, fourth, and sixth deciles in 2008 and 2015, decreased by 0.21, 0.09, and 0.29, respectively, while the accessibility level increased for the other decile arrays. Among them, the sixth decile group of urban potential accessibility shows the largest

reduction, with spatial scattering. For cities like Binzhou, Rizhao, Zaozhuang, Puyang, and Ezhou, there is a significant gap between accessibility levels and social needs.

5. Discussion and Conclusions

This study analyzes the spatial and temporal characteristics of China's transportation accessibility and spatial equality through accessibility and social needs. First, it uses the accessibility index (GAT, PA) to explain its spatial variation characteristics. Second, from the three aspects of population, economy, and society, the index system of urban social needs is built, while principal component analysis is used to obtain the index of urban social needs. Finally, the spatial equality problem is explained by combining the coefficient of accessibility variation and the social demand index. The following conclusions were drawn.

1. The high-speed rail greatly improved the country's accessibility level and promoted socio-economic exchanges between regions. It reshaped the spatial pattern of accessibility and formed a high-reliability level zone centered on high-speed rail lines and site cities. Over the past eight years, the accessibility of cities in the coastal areas of the central and eastern regions of China has always held a leading position. However, cities in the west, southwest, and northeastern border regions have improved their accessibility, but their relative rate of change is low, as is their accessibility level.
2. The opening of high-speed railways has, to a certain extent, widened the differences in the spatial distribution of accessibility across the country. Cities with large changes in accessibility are concentrated in high-speed rail stations and railways in the eastern region. At the same time, the impact of high-speed rail on the accessibility of sites to non-site cities is different: the difference in accessibility between the former is lower than that for the latter.
3. There is a significant difference in the spatial distribution of social demand indexes; cities with high social demand indexes generally have higher accessibility. In 2008, the cities with low transportation accessibility and high social demand index were "scattered" in space, mainly in Xinjiang, Qinghai, Yunnan, Sichuan, Heilongjiang, and Guangdong. The overall level of national accessibility was low because the traffic network in China was not complete at that time. By 2015, the cities with a low level of high social demand were "clustered" in the spatial distribution, which is concentrated in Xinjiang, Tibet, Yunnan, Inner Mongolia, Heilongjiang, and other marginal zones, indicating that accessibility is unfair in the space distribution.

The study focuses on the relationship between accessibility and social needs, and illustrates the impact of high-speed rail on China's accessibility pattern and spatial equality. The social demand index in previous research was mainly concentrated on socially disadvantaged groups, such as low-income, disabled, aging, unemployed, and no-car populations. This study selects several factors related to the economy, society, and population, and uses principal component analysis to conduct a comprehensive evaluation of social needs, combining the accessibility spatial distribution and social demand index to further illustrate the equity of traffic spatial distribution. Therefore, it has both reference value and significance for the study of transportation accessibility and spatial equality.

However, there are still some limitations to the study in terms of accessibility and spatial equality. Transportation accessibility and equity not only refer to travel time, cost, and distance between cities, but also accessibility of infrastructure, such as education, medical care, and services. Therefore, future research needs to further improve the accessibility model and social demand indicator system.

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