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Roles of accessibility, connectivity and spatial interdependence in realizing the economic impact of high-speed rail: Evidence from China

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ABSTRACT

The rapid development of high-speed rail (HSR) in China has raised questions about its implications for regional economic growth. Most existing studies take an aggregate approach to quantify the economic impacts of HSR entrance primarily by inspecting the effect of the dummy variable which reflects the existence of HSR service. This paper takes one step further to investigate how network effects play a role in realizing these impacts. In particular, the effects of location endowment characteristics (evaluated by accessibility and connectivity) enabled by HSR development and the spatial interdependent effects (reflected by neighbors' impacts) are examined. Based on the panel data from China during 2007–2015, we find that when these new factors are taken into account, the effect of the HSR dummy variable (reflecting the existence of HSR service) on regional economic growth is insignificant. On the contrary, the effects of both location endowment measurements, accessibility and connectivity in the railway network, and neighboring effects are significant. These important observations imply that: (1) The economic impact of HSR is largely accomplished by improving accessibility and connectivity in the railway network rather than an isolated presence of HSR infrastructure; (2) The accessibility and connectivity of neighboring cities impact the economic growth of one another; (3) HSR development has generated uneven economic growth concerning the cities in different geographic regions and with different population scales; (4) There is a mismatch between where the accessibility improves the most and where unit improvement generates the largest economic growth; (5) Accessibility and connectivity improvement by railway resulted in a smaller increase in economic growth than that of highway, but larger than those by air and water. These implications shed light on policies regarding multi-modal transport system planning, transport infrastructure investment, and HSR development and operations.

1. Introduction

China has the largest operating and planned high-speed rail (HSR) network around the globe with about 28,000 km by the end of 2018, which is almost 41 times that in 2008 (672 km) when the first HSR line between Beijing and Tianjin was launched to traffic. The rapid expansion of the HSR network in China has substantially reduced the travel time between cities. It contributes to mitigating frictional constraints on economic interactions, and thus potentially generates wider economic impacts associated with improved access to resources, markets, technology, and economic mass.

There has been an increasing body of literature studying the economic impact of HSR, however, there is no consensus on either the existence or the magnitude of the impact. Some previous studies established that the development of HSR network significantly escalated the increase of population, employment, gross domestic product (GDP) and local budgets, and land values of cities with HSR service (Bonnafous, 1987; Garmendia et al., 2008; Hernández and Jiménez, 2014). Yet, at

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the national level, some scholars found that the impacts of HSR line were insignificant on the GDP and population growth (Lin, 2017; Pablo et al., 2007) or needs a longer period before a final verdict could be rendered (Chen and Hall, 2012). The magnitude of impact also considerably varies across studies from different economies. For example, it is shown by Lynch (1998) that the TGV Sud-Est HSR in France induced about a 15% increase in the economy. The estimate for China is also around 15% in terms of the effect of HSR on national economic growth according to Meng et al. (2018). In terms of the increasing rate of employment, the estimates for the northern Netherlands and northern Germany are 0.2% and 0.37% respectively (suggested by Evers et al., 1987).

The impact of HSR on the economic disparity is also controversial. Some studies found that HSR enlarged the disparity by providing improved connectivity to core cities or large cities at the expense of smaller cities (Ureña et al., 2009; Vickerman, 2018), and further enhancing the economy of cities or areas with higher level of economic development regardless of HSR, which is referred to as the "tunnel effect" or "polarized effect" (e.g., Bonnafous, 1987; Chen and Hall, 2012; Monzón et al., 2013; Jiao et al., 2016; Chen and Haynes, 2017). In particular, Spiekermann and Wegener (2006) suggested that the HSR network enhances the status of core cities by largely reducing the travel time and travel cost for producers in peripheral cities to transport their products to core cities. This is expected to further enlarge the market within the core areas (Ureña et al., 2009). With regard to China, Ke et al. (2017) found that the majority of Chinese cities that benefited the most from HSR are located in the eastern coastal regions and core urban agglomeration regions. On the contrary, some studies found that HSR lines might decrease the regional economic disparity at national and regional levels, by creating new locational advantages for small cities or peripheral regions with efficient rail services (e.g., Chen and Haynes, 2017). For instance, it is found in Bonnafous (1987) that the development of TGV Sud-Est in France strengthened the status of small cities such as Lille, and Komei et al. (1997) showed that the expansion of Shinkansen network in Japan led to regional dispersion from core areas. Similarly, the expansion of HSR in China is expected to stimulate economic growth in the second- and third-tier cities via rising real estate prices (Zheng and Kahn, 2013).

The complexity of the mechanism that HSR impacts the economy has been acknowledged as the major factor for the abovementioned variations (e.g., Chen et al., 2016). Building on many previous studies (e.g., Banister and Berechman, 2003), Fig. 1 shows the general mechanism that the transportation sector, including the HSR industry, interacts with economic activities. There are primarily two channels. As the direct channel, the introduction of transportation could promote the development of industries centered around transportation construction, and the land-use patterns (Chen and Haynes, 2015). In another vein, transportation could influence the economic growth at national and city levels by shortening the travel time, reducing the travel cost, and enhancing the accessibility and connectivity (Vickerman, 1999; Gutiérrez et al., 1996; Jiao et al., 2014; Shaw et al., 2014; Chen and Haynes, 2017), which reflect the location endowment of cities in the transport network. Moreover, the enhanced location endowment caused by the operation of transportation could generate several economic effects: improved mobility of production factors (e.g., labor, capital, information, and technology), better productivity, a higher level of investment, wider markets, increased specialization and economies of scale, and the reorganization and rationalization of production (Olsson, 2009), and further influence the interaction of both short-run and long-run effects at the macro-level (Chen and Haynes, 2015, 2017; Jia et al., 2017). Similar mechanisms have been verified by empirical studies on the economic impacts of other transport modes, such as those of aviation services (Baker et al., 2015; Wang et al., 2019; Zhang and Graham, 2020) and those of highway network developments (Bonnafous, 2015; Iacono and Levinson, 2016; Chakrabarti, 2018).

Most existing studies that address the economic impact of HSR take an aggregate approach, while the underlying mechanism through which the impact is realized remains somewhat understudied. This paper attempts to bridge this gap by investigating the effects of location endowment characteristics (evaluated by accessibility and connectivity) and spatial interdependence (reflected by neighbors' impacts). This paper employs econometric models to examine the impact of HSR on economic growth through the improvement of accessibility and connectivity, identify the autocorrelation between neighboring cities, and recognize the variation of HSR's impact in different regions and with different population scales. The impact of HSR is then compared with those of highway, air, and water transportation networks in comparable metrics.

This study contributes to the existing literature in several ways. Firstly, this is the first in the literature that introduces both accessibility and connectivity to characterize the location endowment of cities in the HSR network and examines the effect of location endowment on economic growth. From the theoretical perspective, Jia et al. (2017) and Meng et al. (2018) explored the relationship between the changes in location endowment caused by HSR lines and economic growth. This is adopted in empirical studies of Chen and Haynes (2017), Wang (2018), and Jia et al. (2017), respectively, who introduced accessibility and train frequency as the proxies of location endowment. Only one aspect of location endowment, either accessibility or connectivity, is considered in each study. However, the accessibility and connectivity measure different dimensions of location endowment, which respectively reflect

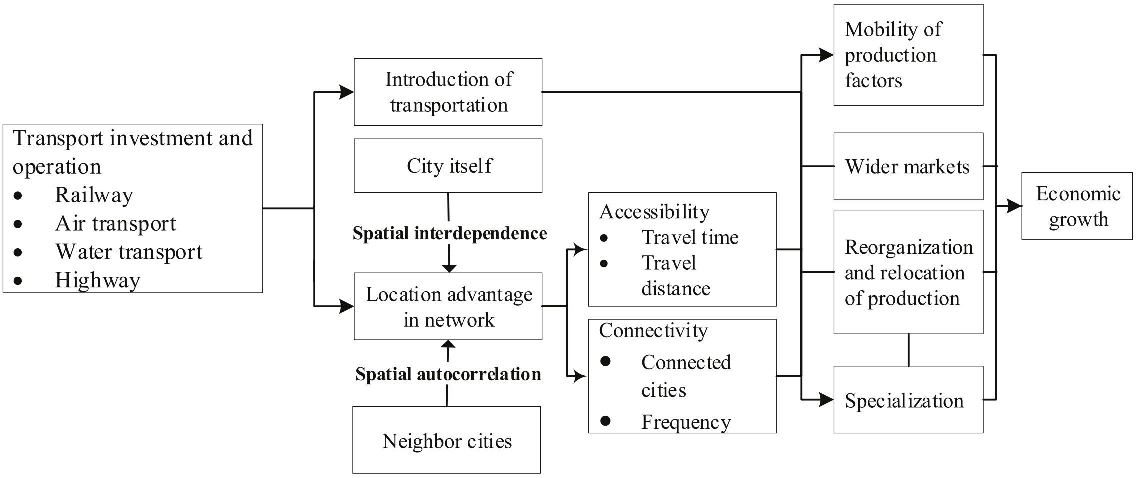

Fig. 1. Theoretical framework of the economic impacts of transport development.

how well a city is located or connected in the transport network. Therefore, it is significant to include both of them in the gauge of location endowment.

Secondly, this paper establishes that, for the first time in the empirical literature, the economic impact of HSR is primarily accomplished by improving the accessibility and connectivity in the railway network rather than the existence of HSR infrastructure. Many previous studies found a significant positive impact of HSR on economic growth through an aggregate analysis where the only variable of interest is the dummy variable representing the introduction of HSR. Our analysis, building on a more specific spatial economic model, shows that the effect of the HSR dummy variable is insignificant when the location endowments are taken into account. On the contrary, the effects of both the location endowment metrics (accessibility and connectivity) in the railway network are significant.

Thirdly, this paper identifies the neighboring effect on the economic impact of HSR. In the context of general economic activities, Bai et al. (2012) found that attributes of neighbor cities might influence the economic growth of one another. However, very limited attention has been paid to the spatial interdependencies or neighboring effects underlying the economic impact of HSR. In this paper, we introduce spatial econometric models to probe the neighboring effect associated with the economic impact of HSR at the national, regional and city levels, respectively. We find that the spatial interdependency exists in the economic impacts of the accessibility and connectivity by the railway network. This means that the economic growth of proximate cities is closely correlated in the development of the location endowment of its neighbors.

Fourthly, previous studies noted that HSR's influence may differ in various cities, especially for large versus small cities; however, as they mainly focused on the overall effect or specific railway lines, a gap analysis of cities with different population scales in different regions is lacking. In this paper, we hypothesize that the influence of HSR lines on economic growth differs across regions as well as cities with different population scale. We find that the improvement in accessibility caused by HSR lines has a larger influence on cities in the western region and medium-sized cities than other regions and other types of cities.

Finally, the economic impact of HSR is compared with other major transport modes (highway, air, and water). While similar mechanisms to that in Fig. 1 have been adopted in the literature to explain the interaction between economic growth and various transportation systems, their effects might be different, influenced by their different technical and economic characteristics. There have been many studies looking at the impacts of HSR on the other transportation modes (e.g., Fu et al., 2012; Li and Sheng, 2016; Wan et al., 2016; Zhang and Zhang, 2016; Jiang and Zhang, 2016; Zhang et al., 2018; Li et al., 2019; Zhang et al., 2019b). For example, the HSR lines have generated a large influence on the air travel passengers, air seats, air routes and travel distance (Wang et al., 2017a; Zhang et al., 2018, 2019a; Liu et al., 2019). However, no one has systematically compared the economic impacts of different transport modes. This paper reproduces the developments of these major transport modes during the same period and finds that the effects of percentage accessibility/connectivity improvement by HSR on economic growth are smaller than that by highway but larger than those by air and water.

The remainder of the paper is organized as follows: Section 2 introduces the methodological framework. Section 3 presents the descriptive statistics and the changes in accessibility and connectivity in different transportation networks. Section 4 presents the assessment results of the economic impact of HSR. Section 5 compares the economic impacts of different transportation services. Section 6 concludes the paper.

2. Methodological framework

2.1. Econometric methods

The Ordinary Least Square (OLS) estimator is widely used in the literature to explore the economic impacts of transportation infrastructure (Jiwattanakulpaisarn et al., 2011; Douglas, 1995; Anselin, 2003; Tong et al., 2013) with controls of demographical and economic variables using panel data. Following this line, we introduce Eq. (1) as the baseline model, which estimates the effect of transport service change on economic output using OLS.

As introduced in Section 1, the economic output of a city can be further affected by attributes of neighboring cities, which is referred to as the neighborhood effect or the spatial autocorrelation. To capture the spatial autocorrelation, three spatial econometric models, namely spatial Durbin model (SDM), spatial lag model (SLM) and spatial error model (SEM), are introduced in Eqs. (2)–(4). The three models have different physical meanings and economic implications. Specifically, the SDM accommodates the spatial interaction effects from both the dependent variable and the explanatory variables. Hence, the SDM can decompose the multi-fold impact of a city on its neighbor's economic output, driven by economic growth, transport location, and other explanatory variables (e.g. labor and investment), respectively. Differently, the SLM and SEM each only account for one aspect of the spatial interaction effect, i.e., SLM only incorporates the neighboring effect of the dependent variable (economic output), and SEM captures that of the error term only (refer to Elhorst, 2010 for a more detailed discussion of the three models). To identify a suitable specification among the SDM, SLM, and SEM, several specification tests will be conducted (refer to Appendix A for specific tests and results).

The Baseline model, SDM, SLM, and SEM are formulated in Eqs. (1)–(4), respectively:

$$\text{Baseline (OLS)}:\ lnY_{i,t}=\beta_0+\beta_1 lnT_{i,t}+\beta_2 lnX_{i,t}+\varepsilon_{i,t} \tag{1}$$

$$\text{SDM}:\ \mathrm{ln}Y_{i,t}=\rho\sum_{j=1}^{n}W_{i,j}lnY_{j,t}+\beta_0+\beta_1 lnT_{i,t}+\beta_2 lnX_{i,t}+\theta_1\sum_{j=1}^{n}W_{i,j}lnT_{j,t}+\theta_2\sum_{j=1}^{n}W_{i,j}lnX_{j,t}+\varepsilon_{i,t} \tag{2}$$

$$\text{SLM}:\ \mathrm{ln}Y_{i,t}=\rho\sum_{j=1}^{n}W_{i,j}lnY_{j,t}+\beta_0+\beta_1 lnT_{i,t}+\beta_2 lnX_{i,t}+\varepsilon_{i,t} \tag{3}$$

$$\text{SEM}:\ \mathrm{ln}Y_{i,t}=\beta_0+\beta_1 lnT_{i,t}+\beta_2 lnX_{i,t}+(1-\gamma W)\varepsilon_{i,t} \tag{4}$$

where $Y_{i,t}$ is gross domestic product (GDP), which reflects the economic output of city i at time t; $T_{i,t}$ represents the general determinants for a transport mode (e.g., rail, highways, aviation, and water). $X_{i,t}$ represents the labor and capital variables. β represents the corresponding parameters of each variable; ε is the residual with a zero mean and constant variance.

The dependent variable, gross regional product, can be driven by a variety of factors. Labor and investment are commonly regarded as the basic factors, which are widely used in the production function model to examine the influence on productivity, and so forth the overall economic performance. Building upon the basic production model, Douglas (1995) and Anselin (2003) extended the model to incorporate transport variables as an external factor to productivity. Following this approach, this study recruited the labor, capital and transport variables, represented by the employment, total investment in fixed assets and the locational advantage in the transport network respectively, as explanatory variables for the economic performance of a region. The locational advantage in the transport network is measured by the accessibility or connectivity enabled by the specific transport service, which will be introduced in Section 2.2. Moreover, the robustness of the selected spatial model is examined and discussed in Appendix B.

Eqs. (2)–(4) involve terms with W, in which W represents the weight matrix. It is evaluated by the spatial adjacency matrix of each city.[1] In the spatial adjacency matrix, the weight is set to 1 when two cities own common edges spatially and is set to 0 otherwise. In particular, $\sum_{j=1}^{n} W_{ij} lnY_{j,t}$ characterizes a spatial lag in the dependent variable $Y_{j,t}$, which represents the spatially weighted average value of economic growth from i's neighboring cities at time t; $\sum_{j=1}^{n} W_{ij} lnX_{j,t}$ is a spatial lag in the labor and capital variables; Similarly, $\sum_{j=1}^{n} W_{ij} lnT_{j,t}$ is a spatial lag in the transportation variables. The coefficients ρ, θ_1 and θ_2 represent the effects of neighboring cities' economic growth, the labor and capital variables and the transportation variables on the economic growth of city i, respectively; and γ represents the spatial lag of the associated residual.

2.2. *Location endowment indicators in transport networks: accessibility and connectivity*

Accessibility is defined as the potential for opportunities for interaction (Hansen, 1959), and can be used to reflect how well a city is located in the transport network. According to the characteristics of the infrastructure network, the physical/infrastructure transport network could be divided into two categories: the point infrastructure (e.g., airports and water ports) and the network infrastructure (e.g., railway and highway). Traditionally, the accessibility of point infrastructure is evaluated using the travel time to the nearest airports or water ports (Jin et al., 2008); while the accessibility of network infrastructure could be explored using the shortest travel time between two cities (Jiao et al., 2014). In particular, the travel time to the nearest airports or water ports, and the shortest travel time between two cities by highway, a door-to-door transportation mode, are used to calculate the accessibility of cities by different transport modes. The travel time to the nearest airports or water ports is collected using the Baidu API (http://lbsyun.baidu.com/). The shortest travel time between two cities by highway can be calculated based on the operating speed and route distance by highway using the network analysis in ArcGIS following a previous study by Jiao et al. (2014).

While HSR considerably shortens the travel time between cities (Xu et al., 2018a,b), the change to the conventional railway is much less during the same period of time. Conventional railway has experienced electrifications, speed-ups, and expansions to small cities. However, most of the electrified and speeded railway lines are in parallel with HSR lines, hence its influence on the accessibility is marginal when treating the railway network as a whole. Given these considerations, we consider the railway as one mode and refer to 'railway' and 'HSR' interchangeably in this paper.

Considering that most of the newly constructed HSR stations located outside the traditional city center, the shortest travel time between two city centers (administrative centers) by railway is defined as:

$$T_{ij}^{H} = t_{ik} + t_{waiting} + t_{kp} + t_{leaving} + t_{pj} \tag{5}$$

where T_{ij}^{H} is the shortest travel time between city i and city j by railway; t_{ik} is the access travel time from the city center of origin to the nearest railway station, $t_{waiting}$ is the waiting time in a railway station, t_{kp} is the travel time between two railway stations, $t_{leaving}$ is the egress travel time from a railway station, and t_{pj} is the travel time from the railway station to the city center of the destination. Amongst, the travel time between the city centers of origin/destination and the railway station by urban transport network is collected using the Baidu API, and the shortest travel time between two railway stations is calculated according to the train timetable of China.

To explore the accessibility of cities in railway network and highway network, the weighted average travel time (WATT), a widely-used accessibility indicator, is introduced (Gutiérrez et al., 1996; Vickerman, 1999; Wang, 2018). WATT calculates the average travel time between one city and all the others weighted by the mass of destinations (measured by the square root of the product of the population and GDP in this study). The formula is given by

$$\mathrm{WATT_i} = \frac{\sum_{j=1}^{n} (\mathrm{T_{ij}} \times \mathrm{M_j})}{\sum_{j=1}^{n} \mathrm{M_j}} \tag{6}$$

where $WATT_i$ is the weighted average shortest travel time of city i. T_{ij} is the shortest travel time between city i and city j; M_j is the attribute of city j, which is defined by the square root of the product of the population and GDP. It is noteworthy that the smaller value of $WATT_i$ means shorter average travel time to all destinations which implies better accessibility of city i.

The connectivity of a city reflects how well it is connected to the transport network (Willigers and Wee, 2011). The connectivity of cities in the airline network, highway network, water network and railway network could be evaluated by either service frequency or passenger flow of airlines, inter-city bus, water and railway respectively (Mo et al., 2008). However, it is hardly possible to collect data of the timetable of inter-city bus and water services in the sampling period. Some existing studies show that the highway density, the volume of passenger aviation traffic, and the volume of freight traffic by water (Jin et al., 2008; Mo et al., 2008) normally positively correlates with the connectivity calculated through timetables of each transport mode. Therefore, the density of highways, the volume of passenger aviation traffic, and the volume of freight traffic by water are employed as the measurements of connectivity of cities in the transport network of highway, air, and water respectively.

The connectivity of a city in the railway network is measured by the train frequencies going through the city (Chen and Hall, 2012) and the weighted degree centrality in the passenger train network (Jiao et al., 2017). The weighted degree centrality (WDC) is introduced as the connectivity measurement, which couples the service frequencies with the number of direct destinations in the railway network. The formula of WDC is given by

$$\mathrm{WDC_i} = \mathrm{k_i^{\alpha}} \cdot \mathrm{s_i}^{1-\alpha} \tag{7}$$

where WDC_i is the weighted degree centrality (WDC) of node i and the larger value of WDC_i means the better connectivity of city i in the transport network; k_i is the number of cities directly connected with city i by railway, s_i is the train frequency going through city i, and α is the coefficient representing the weights of the two measurements. Following Jiao et al. (2017), α is set to be 0.5 in this study, which means that the train frequency and the number of direct destinations are weighted equally in the connectivity measurement. The robustness is verified by varying the value of α among 0, 0.1, 0.3, 0.5, 0.7, 0.9 and 1. We find that there is little influence on the estimates of economic impacts of WDC, as shown in Appendix C.

3. Data and descriptive statistics

3.1. *Data and variable description*

The first HSR line of China was opened in 2008, which runs between Beijing and Tianjin. Afterward, it experienced rapid development, with

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[1] Alternatively, the weight matrix can be built based on the inverse distance between cities, which can be measured by the Euclidean distance, the transport distance, or the travel time (e.g., Bottasso et al., 2014; Feng et al., 2019). Since the travel time (a form of distance) has been incorporated in the accessibility indicators, this study adopts the spatial adjacency matrix to eliminate the mutual interference.

the mileage of HSR lines increased from 672 km in 2008 to about 28,000 km in 2018. While HSR considerably shortens the travel time between cities, the change to the conventional railway is much less during the same period of time, in terms of the impact on overall accessibility of the railway mode.

During this period 2008–2018, air transport has opened its civil aviation sector to private investors and the number of private airlines grew rapidly, with the new airlines expanding the local market (Wang et al., 2016). The domestic navigable airports increased from 158 in 2008 to 202 in 2018. In addition, there is another trend for air transport, which is the development of low-cost carriers. The development of low-cost carriers in China could date back to 2005, when the first LCC (named Spring Airlines) put into commercial operation. Although the policy of the Civil Aviation Authority of China (CAAC) has turned to the free market since 2003, authorities have engaged reforms towards a kind of state-managed domestic free market whose core goal is to strengthen the so-called Big Three (namely, Air China, China Southern, and China Eastern) (Zhang et al., 2014b; Dobruszke and Wang, 2019). Influenced by this, the market share of LCCs in China is relatively lower than that in the globe. For example, the market share of LCCs concerning the passenger traffic in China was just 10.3%, which was lower than that in the global market (25.7%), and much lower than that in North America (31%) and Europe (almost 40%). The market share changes to 3.6% concerning the number of air routes (Dobruszke and Wang, 2019).

The panel data of this study contains 333 prefecture-level cities and four municipalities of China from 2007 to 2015. Since the first HSR line was opened in 2008 between Beijing and Tianjin, the sampling period is from 2007 to 2015 in this study. According to the population scale of cities, the 337 cities in China are categorized into four tiers according to their population scale in year 2015: 23 megacities (with populations of over 3 million), 110 large cities (1–3 million), 117 medium cities (0.5–1 million), and 87 small cities (below 0.5 million). According to the location of cities, the 337 cities in China are categorized into three regions: 101 cities in the eastern region, 117 cities in the central region, and 119 cities in the western region. The categorization of study objects is summarized in Table 1.

The networks of HSR, expressway, airports and water ports in 2015 are shown in Fig. 2. All the demographic and economic data, such as GDP, employment, total investment in fixed assets, mileage of road, passenger flows by air and cargo flows by water, etc., are sourced from the "China's Regional Economic Statistical Yearbook (2004–2014)", "China City Statistical Yearbook (2004–2016)" and the corresponding provincial statistical yearbooks. Considering the collinearity and data availability, some other factors influencing economic growth, including population, industrial structure, research and development (R&D), human capital, are not chosen in this paper. Basic transport data, including expressways, national roads, provincial roads, county roads, urban roads, and administrative divisions, are mainly obtained from the Thematic Database for the Human-Earth System of the Chinese Academy of Sciences, the 1:4 M Database of the National Fundamental Geographic Information System of China and the open-street database (http://www.openstreetmap.org). The train frequencies and the number of direct destinations are calculated according to the national railway passenger train schedules, provided by Railway China (www.12306.cn). The annotations and associated descriptive statistics are summarized in Table 2.

Table 1
Categorization of study objects.

	Categories	Standards	No. of cities
By population scale	Megacities	More than 3 million people in the urban districts	23
	Large cities	1-3 million people in the urban districts	110
	Medium-sized cities	0.5–1 million people in the urban districts	117
	Small cities	Less than 0.5 million people in the urban districts	87
By geographic location	Eastern region	Located in Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Guangzhou and Hainan province and Beijing, Tianjin, and Shanghai	101
	Central region	Located in Shanxi, Henan, Heilongjiang, Jilin, Hubei, Hunan, Jiangxi, Inner Mongolia, and Anhui province	117
	Western region	Located in Shaanxi, Sichuan, Xizang, Xinjiang, Ningxia, Qinghai, Yunnan, and Guangxi province, and Chongqing	119

3.2. Improvement of accessibility in different transport networks

In this section, we analyze the improvement of accessibility caused by the developments of the four transportation modes, railway, highway, aviation, and water. Table 3 presents the statistics of the improvement. Since there was little change in the network of water ports in China during 2007–2015, the improvement in accessibility in terms of the water mode is zero as shown in Table 3. The spatial distribution of the accessibility improvements enabled by different modes is relayed to Appendix D.

It is shown in Table 3 that the development of the HSR network in China led to a 32.15% increase in accessibility at the national level during 2007–2015. However, the HSR expansion generated uneven "time-space convergence" region-wise. It is shown that the eastern region experienced the largest improvement in accessibility, followed by the central and western regions in China.[2] Specifically, the accessibility increased by 36.52% in the eastern region, superior to the central (33.74%) and western (26.87%) regions respectively. In another vein, the magnitude of accessibility improvement was in line with the population scale – megacities had the highest improvement in accessibility, followed by large cities, medium-sized cities, and small cities. Specifically, the accessibility increased by 38.15% in megacities, which is equivalent to 1.11 times the increasing rate of large cities, 1.16 times medium-sized cities, or 1.42 times small cities. Therefore, the change of accessibility brought by HSR development is in line with the spatial distribution of population and GDP in China.

Compared with other transport modes, the expansion of the HSR network in China has generated the largest improvement in accessibility among the transportation modes (railway, aviation, and highway) at the national scale. Specifically, the development of HSR lines led to a 32.15% increase in accessibility, followed by aviation (8.67%) and highway (6.35%). A similar result can be found when comparing the modes in different city categories. Across the various subsamples spanned by geographic regions and city categories, the western region, and large cities witnessed the largest accessibility improvement brought by the development of HSR, followed by highway and aviation. The reason might be that the focus of highway development during this period was on building parallel lines and repairing dead-end highways, which had little influence on accessibility between cities. During the same period, the number of airports increased from 148 to 217, and the mileage of HSR lines increased from 484 km to 19838 km in China.

In terms of geographic regions, cities with a large increase in accessibility caused by HSR lines were mainly located along HSR lines in the eastern and central regions, while those caused by highway and aviation mostly concentrated in the central and western regions. As the overall effect, the evolved HSR network generated the highest improvement in accessibility in the eastern region, and the maximum

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[2] The accessibility/connectivity increase in the eastern/central/western region refers to the average accessibility/connectivity improvement of cities in the region.

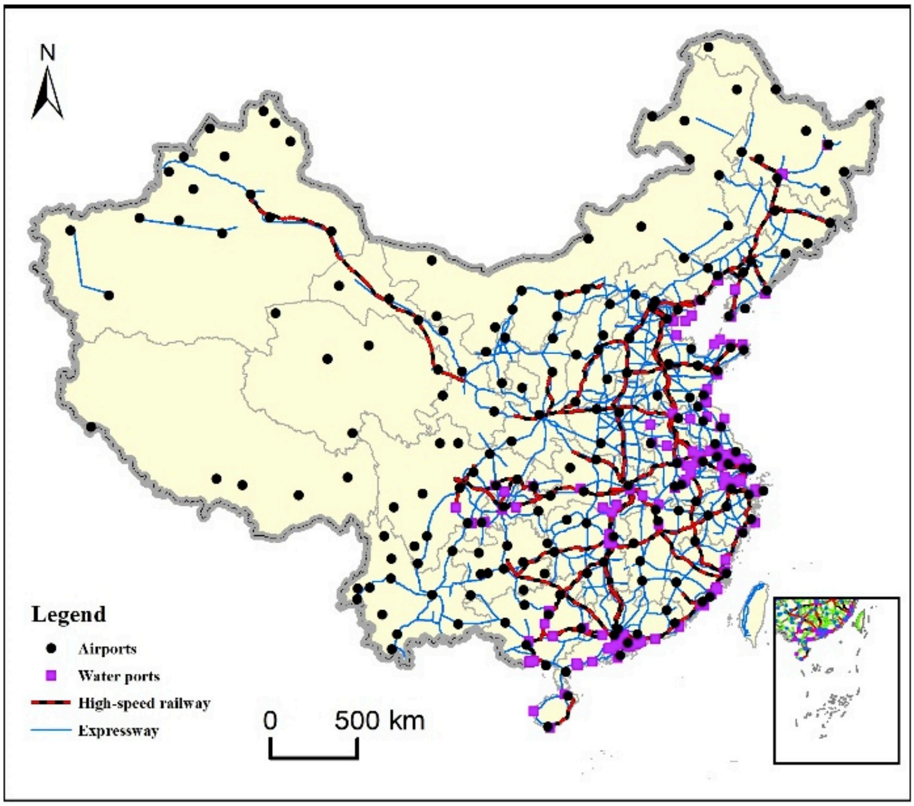

Fig. 2. Networks of HSR, expressway, airport and water port in China as of 2015.

Table 2
Description of variables in the models.

Variables			Description	Mean	Standard deviation	Min	Max
Economic growth		Gross Sdomestic product (Y)	Constant price of 2000 RMB (Billion Yuan)	95.56	140	7.7	1454
External	Labour	Employment (E)	Million persons	2.28	18.83	3.2	16.68
	Investment	Total investment in fixed assets (FI)	Constant price of 2000 RMB (Billion Yuan)	57.03	72.68	0	895.35
Transport	HSR availability	Dummy (HSR)	Equals one for cities that have HSR services and zero otherwise	0.26	0.44	0	1
	Accessibility	Railway (RA)	Weighted average travel time (hours)	14.28	6	7.48	49.09
		Highway (HA)	Weighted average travel time (hours)	17.96	6.02	11.9	50.26
		Aviation (AA)	Shortest travel time to the nearest civil airports (hours)	1.12	1	0	15.19
		Water (WA)	Shortest travel time to the nearest ports (hours)	4.74	7.24	0	41.64
	Connectivity	Connectivity in the railway network (RC)	Weighted degree centrality in passenger train network	191.16	201.71	0	1188.08
		Highway density (HD)	Total miles of highway divided by country's land area (km/km^2)	0.89	0.54	0	4.75
		Passenger traffic flow by aviation (AC)	(10,000 persons)	186.11	748.08	0	9918.89
		Freight traffic flow by water (WC)	(10,000 tons)	1300.17	4434.64	0	135708

Note: dummy 1 HSR, 0 railway. Due to data availability, the connectivity of cities in the transport network of highway, air, and water are substituted by the highway density, passenger traffic flow by aviation, and freight traffic flow by water.

occurs in the central and the western regions respectively concerning the aviation and highway. The reason might be that the HSR lines expanded rapidly in the eastern and central regions during 2007–2015, while the highway and airports have formed mature networks in the eastern and central regions, and began to expand in the western region of China. Most of the emerged airports are located in the western and central regions, in particular in the small and medium-sized cities in these regions.

In terms of population scale, megacities experienced the largest improvement in accessibility caused by HSR lines, while the accessibility improvements brought by highway and aviation are mostly felt in small cities. Given by highway expansion, the accessibility increased by 6.5% in small cities, followed by large cities (6.38%), medium-sized cities (6.36%) and megacities (5.56%). Small cities also benefited the most from the increase in accessibility caused by aviation development, followed by medium-sized cities, megacities and large cities. Therefore, while megacities experienced the largest increase in accessibility through the railway network, small cities had the greatest accessibility via highway and aviation networks during 2007–2015.

Table 3

Improvement in accessibility and connectivity during 2007–2015.

		Accessibility improvement (%)				Connectivity improvement (%)			
		HSR(Railway)	Highway	Aviation	Water	HSR(Railway)	Highway	Aviation	Water
National level		32.15	6.35	8.67	0	167.03	36.06	278.14	255.19
By geographic region	Eastern region	36.52	5.91	10.75	0	115.34	21.52	122.99	125.60
	Central region	33.74	6.39	12.59	0	242.55	30.88	523.90	562.09
	Western region	26.87	6.67	3.07	0	136.65	53.48	168.21	63.42
By population scale	Megacities	38.15	5.56	9.53	0	108.27	15.33	118.06	56.27
	Large cities	34.37	6.38	3.68	0	281.28	29.30	492.29	240.62
	Medium-sized cities	32.77	6.36	13.30	0	110.38	35.63	195.24	486.87
	Small cities	26.92	6.50	17.85	0	114.28	50.65	161.19	14.61

3.3. *Improvement of connectivity in different transport networks*

This section discusses the improvement of connectivity caused by the developments of the four transportation modes. The average percentage change in connectivity of cities in each subsample through different transport networks is presented in Table 3. The spatial distribution is relayed to Appendix E.

Table 3 shows that the expansion of HSR network in China largely increased the connectivity of cities in the railway network during 2007–2015, but the increase in connectivity distributed unevenly in space. The HSR lines improved the connectivity at the national level by 167.03%, which is higher than the accessibility increase (32.15%). In terms of geographic regions, the central region experienced the highest increase in connectivity caused by the development of HSR lines, followed by the western and eastern regions, which is different from the trend of accessibility improvement. Specifically, the connectivity caused by HSR lines in the central region increased by 242.55% during 2007–2015. The increasing rate is 1.77 times of that in the western region or 2.1 times of the eastern region. In terms of population scales, large cities had the highest increase in connectivity caused by HSR lines, followed by small cities, medium-sized cities, and megacities. Specifically, the connectivity increased by 281.28% for the large cities caused by HSR lines, which is 2.46 times that of small cities, 2.55 times that of medium-sized cities, or 2.6 times that of megacities. Overall, the growing HSR network brought the largest connectivity improvement to cities in the central region and with a population of 1–3 million, which is different from the trends of accessibility improvement.

Compared with other transport modes, the increase in connectivity caused by HSR is lower than those by water and aviation, but higher than that by the highway at the national level (see Table 3). The average increase in connectivity caused by HSR lines is 167.03%, which is 60% of that by aviation, 65% of water, or 4.63 times of highway. The similar trends could be found in the eastern and central regions and for medium-sized cities. However, the connectivity in the western region and for megacities, large cities, and small cities also had the largest increase caused by aviation, but the improvement in connectivity caused by HSR ranked the second, followed by water and highway. Overall, the effects of HSR lines on connectivity by railway is lower than that by aviation and higher than that by highway.

In general, distributions of the connectivity increments brought by other transport modes deviate from that of railway as shown in Table 3. Specifically, cities located along HSR lines, with the population scale between one and three million had the largest increase in connectivity caused by HSR. The increase in connectivity caused by highway in the western region (53.48%) is higher than that in the central (30.88%) and eastern (21.52%) regions; the connectivity caused by highway increased greatest for small cities (50.65%), followed by medium-sized cities (35.63%), large cities (29.3%) and megacities (15.33%). The increase in connectivity caused by water in the central region (562.09%) was greatest, exceeding that of the eastern region by 3.48 times and that of the western region by 7.86 times. The rank of accessibility increase caused by water was medium-sized cities, large cities, megacities, and small cities. A similar trend could be found in terms of the enhanced connectivity caused by aviation, but the degree of improvement is much higher than that caused by HSR lines.

4. Impact of HSR on economic growth: the econometric estimation

This section examines the impact of HSR on regional economic growth using econometric methods. Based on the spatial models established in Section 2.1, several statistical tests are conducted to inform the choice of an appropriate model specification (refer to Appendix A for detailed model selection criteria). To determine whether spatial fixed effects, temporal fixed effects, or both should be included in the model, we conduct a likelihood ratio (LR) test and find that the spatial fixed effect should be included in the model. Through the Lagrange Multiplier (LM) test and Wald test, we find that the spatial Durbin model (SDM) specified in Eq. (2) is preferred over the spatial lag model (SLR) and spatial error model (SEM) to characterize the economic impacts of HSR concerning the spatial autocorrelation effects. This implies that the neighboring effects of the economic growth, transport location and the other explanatory variables all prevail in the data. The test results regarding the model selection and robustness verification are provided and discussed in Appendixes A and B.

The following analysis employs the SDM with a spatial fixed effect. The estimation results are presented in Table 4. The spillover effects of HSR-related variables, i.e., the HSR dummy and accessibility and connectivity in railway networks, are discussed in the following subsections to illustrate the impacts of HSR on economic growth.

4.1. *Impact of HSR dummy*

According to the SDM results presented in Table 4, the HSR dummy variable and its spatial lag have no significant influence on GDP in terms of either the national or regional average. While many previous studies warranted the significant positive impact of HSR on economic growth (Chen and Haynes, 2017; Chen et al., 2016), most of them adopted an aggregate treatment that only a dummy variable indicating the existence of HSR is included in the econometric model. The impact of HSR in our analysis, however, is disaggregated into the effects of accessibility, connectivity, and/or spatial autocorrelation. Thus, the insignificance of the HSR dummy implies that HSR may impact the economic growth through location endowments or neighboring effect, rather than an isolated existence of HSR infrastructure.

In subsamples spanned by various population scale, the HSR dummy variable showed a positive influence on GDP of megacities, but a negative influence on GDP of large cities and small cities according to the SDM. This finding indicates that the introduction of HSR service largely promoted the economic growth of megacities but had a negative influence on the economic growth of small cities. The connection of HSR lines between small cities and megacities might drive the high-quality production factors moving from the small cities to the megacities and enlarge the market areas of megacities, and thus promote the economic growth of megacities by the expense of small cities.

The coefficient of the spatial lag of HSR dummy represents the

Table 4
Estimation of HSR's impacts on economic growth using SDM with fixed effect at city levels.

		Accessibility improvement (%)	Connectivity improvement (%)	SDM					
				HSR Dummy	log (RA)	log(RC)	W*HSR Dummy	W*log (RA)	W*log (RC)
National level		32.15	167.03	−0.026	−1.232***	0.001**	0.005	0.181***	0.001
By geographic regions	Eastern region	36.52	115.34	−0.043	−0.881***	0.003	−0.009	−0.132***	0.002***
	Central region	33.74	242.55	−0.024	−0.856***	0.004***	0.001	0.127***	0.001***
	Western region	26.87	136.65	−0.036	−1.667***	0.002	−0.01	0.190***	−0.001
By population scale	Megacities	38.15	108.27	0.003**	−0.905***	0	0.015***	0.174***	−0.002**
	Large cities	34.37	281.28	−0.020***	−0.901***	−0.002***	0.002	0.205***	0
	Medium-sized cities	32.77	110.38	−0.001	−1.374***	0.003	0.002	0.217***	0.001**
	Small cities	26.92	114.28	−0.061***	−0.692***	0.004***	−0.013**	0.084***	0

Notes: Significance level: ***<0.01, **<0.1.

impacts of the introduction of HSR lines in a city's neighbors on its economic growth; thus, a positive coefficient means that the introduction of HSR lines in a city's neighbors has a positive influence on its economic growth. The spatial lag of the HSR dummy for megacities had a positive and significant influence on GDP, whereas that for small cities was significantly negative, which indicates that GDP for megacities could be positively influenced by the introduction of HSR service of its neighbors, while that for small cities could be negatively impacted.

4.2. *Impact of accessibility*

It is shown in Table 4 that the accessibility in railway made a positive contribution to economic growth at national, regional and city levels in China, but the magnitude of impact varies across regions according to SDM. Specifically, the elasticity of accessibility by railway on economic growth was −1.232 according to SDM, which suggests that a 1% increase in accessibility could lead to 1.232% increases in GDP. At the regional level, the western region had the highest increase in GDP caused by improved accessibility by rail, followed by the eastern and central regions. Specifically, a 1% improvement in accessibility by railway could generate a 1.667% increase in GDP in the western region, which is 1.89 times that in the eastern region, and 1.94 times that in the central region. The variation is divergent from that of the accessibility increase among regions, which decreases from the eastern region to the central and western regions. This is to say, the western region with the smallest improvement in accessibility obtained the largest economic growth stimulated by that small improvement. The location endowment of cities in the western region mainly lagged behind economic growth (Jiao et al., 2016), and a small increase in accessibility might generate a large influence on economic growth. On the contrary, eastern cities have developed transport infrastructure in earlier stages, and the recent change in accessibility has less influence on their economic growth. This finding is consistent with the theoretical framework of Wolfram (2003) who suggested that the improvement in transportation played a facilitating role in the regions with both higher accessibility and GDP, a catalyst role in the regions with relatively lower accessibility and lager GDP, a negative role in the region with both lower accessibility and GDP, and was not relevant in the regions with relatively higher accessibility and lower GDP.

In terms of population scale, medium-sized cities experienced the largest effect of railway accessibility improvement on GDP, followed by megacities, large cities, and small cities. This is also divergent from the variation of region-wise accessibility change. Specifically, a 1% improvement in accessibility by railway might generate a 1.374% (SDM) increase in GDP for medium-sized cities, which is 1.23 times that for megacities, 1.24 times that for large cities, and 1.61 times that for small cities, respectively. Though larger cities experienced the highest increase in accessibility, the economic impacts of accessibility are the lowest. The economy of medium-sized cities, however, is more sensitive to the change of accessibility in the railway network. This can also be explained with the theoretical framework of Wolfram (2003). A large number of medium-sized cities are located in the central and western regions with less developed transport infrastructure, and thus the economy is more sensitive to the change of accessibility. On the contrary, the majority of large cities are located in the eastern region with developed transport infrastructure where economic growth is less sensitive to transportation.

The coefficient of the spatial lag represents how the accessibility of neighboring cities impacts the economic growth of one another; thus, a positive coefficient means that the improvement of accessibility of a city's neighbors has a negative influence on its economic growth. It is found in Table 4 that the coefficient of the spatial lag of accessibility, i.e., $W\cdot log\ (RA)$, is negative for the eastern region and positive for all other city categories. This implies that the improvement in accessibility of a city's neighbors might have an overall positive influence on GDP in the eastern region, but an overall negative influence on other city categories. It means that the larger increase in accessibility of its neighbors, the larger benefit could HSR generate on the economic growth of one particular city in the eastern region, and vice versa for other city categories. The economy of medium-sized cities is the most sensitive to the improved accessibility of their neighbors, followed by large cities, megacities and small cities. Combining the coefficient of accessibility by railway and its spatial lag, the GDP of medium-sized cities is the most sensitive to the improved accessibility of itself and its neighbors, followed by megacities, large cities, and small cities.

4.3. *Impact of connectivity*

According to the SDM estimation results presented in Table 5, the connectivity in the railway network has a significantly positive influence on economic growth at the national level, in the central region, and for small cities, but a negative impact on that for large cities. Specifically, the national-wide elasticity of connectivity by railway on economic growth is 0.001, which suggests that a 1% increase in connectivity leads to a 0.001% increase in GDP. The coefficient of the connectivity in the railway network is 0.004 for the central region subsample, but the coefficient is insignificant for eastern and western region subsamples. Therefore, the central region obtains a significant increase in GDP due to enhanced connectivity in the railway network.

In terms of population scale, the connectivity in the railway network has a negative influence on GDP for large cities but it is positive for small cities. This finding indicates that the enhanced connectivity for large cities might generate a "siphon effect" such that the enhanced connectivity restrains the economic growth of large cities, and that the connectivity improvement stimulates larger economic growth in small cities. The coefficients are insignificant for megacities and medium-sized cities.

The spatial lag of connectivity by railway $W\cdot log\ (RC)$ reflects how the connectivity of neighboring cities impact the economic growth of one another. The estimated coefficient is negative for the megacities

Table 5
Comparison of connectivity impacts on economic growth by four transport modes.

		Connectivity				Spatial lag of connectivity			
		Railway	Highway	Aviation	Water	Railway	Highway	Aviation	Water
National level		0.001**	0.028***	0.001***	0.002***	0.001	0.005	0.001***	0
By geographic region	Eastern region	0.003	0.418***	0.004	0.005	0.002***	0.267***	0.005***	0.006***
	Central region	0.004***	0.022	−0.002**	0	0.001***	0.005	0	−0.001
	Western region	0.002	0.019**	0.003***	0.003***	−0.001	−0.002	0.001**	0.001
By population scale	Megacities	0	−0.013	−0.004	−0.002	−0.002**	0.058***	−0.002**	−0.002**
	Large cities	−0.002***	0.008	−0.001	0	0	0.006	0	0
	Medium-sized cities	0.003	0.034	0.001	0.002	0.001**	−0.010**	0.001	0.001
	Small cities	0.004***	0.068***	0	0.001	0	−0.023***	0	−0.002***

Notes: Significance level: ***<0.01, **<0.1.

Table 6
Comparison of accessibility impacts on economic growth by four transport modes.

		Accessibility				Spatial lag of accessibility			
		Railway	Highway	Aviation	Water	Railway	Highway	Aviation	Water
National level		−1.232***	−1.726***	0.014	0.221	0.181***	0.163***	0	0.05
By geographic region	Eastern region	−0.881***	−1.808***	0.024	−0.336	−0.132***	−0.139	0.033**	0.383
	Central region	−0.856***	−1.641***	−0.003	0.505	0.127***	0.182***	−0.006**	0.18
	Western region	−1.667***	−2.359***	0.017***	0.227**	0.190***	0.334***	0	−0.111
By population scale	Megacities	−0.905***	0.083	−0.017	0.31	0.174***	−0.047	−0.032***	−0.081
	Large cities	−0.901***	−1.167***	0.007	0.041	0.205***	0.198***	−0.006**	−0.125
	Medium-sized cities	−1.374***	−1.609***	0.004	−0.038	0.217***	0.224***	0.011***	0.068
	Small cities	−0.692***	−1.246***	0.017***	−0.251	0.084***	0.283***	0.001	−0.124

Notes: Significance level: ***<0.01, **<0.1.

subsample, positive for medium-sized cities and no significant for large cities and small cities. This means that the enhanced connectivity of neighbors generates a positive influence on the economic growth of medium-sized cities, but a negative influence on that of megacities. With regard to the influence in geographic regions, the improvement in connectivity of neighbors positively impacts GDP in the eastern and central regions but has no significant influence on that in the western region.

Comparing the impact of accessibility and connectivity, improved accessibility has a larger influence on economic growth than improved connectivity driven by HSR expansion. Specifically, the coefficient of accessibility is equivalent to 44 times that of the connectivity in railway network at the national level. A similar relationship is valid in all subsamples. This implies that, *ceteris paribus*, the decrease in travel time generates larger economic influence than the enhanced connectivity. Therefore, the government should put more weight on enhancing accessibility rather than connectivity to promote regional economic growth.

5. Comparison with the economic impacts of other major transport modes

This section compares the economic impacts of various transport systems. Following the same process, the SDM is estimated based on the data collected from other modes, i.e., highway, aviation, and water. To focus on the spillover effects of accessibility and connectivity improvements on economic growth, we present in Table 5 and Table 6 the estimation results of accessibility and connectivity-related variables associated with the modes. In Tables 5 and 6, the coefficients of accessibility/connectivity represent the percentage increase of GDP associated with a percentage increase in accessibility/connectivity; the coefficients of spatial lags symbolize the GDP growth associated with a percentage increase in accessibility/connectivity of the neighbor cities.

It is shown in Table 6 that the accessibility improvement caused by HSR has a smaller impact on economic growth than that by the highway in most subsamples. This means that a percentage increase in the accessibility in highway network is associated with larger economic growth than that of HSR. On the contrary, it is shown in Section 3.2 that the highway accessibility has less change than railway during 2007–2015. Such a divergence indicates that the extent accessibility impacts economic growth does not necessarily correlate with the extent of accessibility changes.

Specifically, the accessibility by highway has a significantly positive influence on GDP at the national level, in all the three regions and for the other three types of cities except megacities. As the national average, the effect of accessibility by highway on GDP is −1.726, which is 1.4 times that of accessibility by railway, respectively. With regard to the results from various subsamples spanned by geographic regions and city categories, the effect of accessibility by highway is also higher than that by railway in all subsamples except megacities. The accessibility by air has a significantly negative impact on GDP growth in the western region according to SDM, and for small cities, but the influence strength of accessibility by air is lower than that by railway and highway in terms of accessibility in the western region. The influence of accessibility by water is insignificant in all the subsamples. Moreover, the economic impacts of accessibility in highway and railway have similar spatial distributions across geographic regions, with cities in the western region getting the largest influence on economic growth, followed by the eastern and central regions. With regard to population scale, the GDP of medium-sized cities is the most sensitive to the accessibility increase in railway and highway network, while that of small cities are most sensitive to the accessibility increase in aviation network. In terms of the spatial lag of accessibility, the effect by highway is also higher than that by railway in central and western regions and for medium-sized cities and small cities.

The economic impacts of connectivity by the four transport modes are presented in Table 5. It is shown that the effect of HSR is lower than that by highway and by water at the national level according to SDM. Specifically, the coefficients of connectivity by highway, railway, and air are significantly positive at the national scale, and the elasticity of highway density is 28 times that of connectivity in railway network and 28 times that of passenger flow by air according to SDM. Also, the enhanced connectivity caused by railway is lower than that by highway in the eastern and central regions, for large cities and small cities. The connectivity in the central region by railway generated a larger influence on economic growth than that by water, as there are a few water ports located in the central region of China. With regard to the spatial lag of connectivity, the connectivity of a city's neighbors by highway has the largest influence on economic growth in the eastern region and for megacities, followed by that by water, air, and railway. In addition, the GDP of small cities and cities in the central region are most sensitive to the connectivity increase in railway network and highway network, followed by that of medium-sized and small cities, or by cities in the eastern region. This implies that the GDP of small cities and in the central region are the largest beneficiaries in both highway and railway networks.

6. Conclusions and discussions

This paper provides a systematic analysis of the roles network effects play in realizing the economic impact of HSR. Based on the real data from China during the period 2007–2015, the paper establishes comparable metrics of accessibility and connectivity, reproduces the evolution of HSR network, and identifies the effects of accessibility and connectivity on economic growth. Specifically, the linkages between economic growth at the city level and the location endowment measured by both accessibility and connectivity are examined empirically using SDM. Accessibility (weighted travel time) is adopted as a proxy to reflect how well a city is located in the transport network concerning the characteristics of travel speed, whereas connectivity (weighted degree centrality) is introduced to capture how well the city is connected concerning the service frequencies and connections between cities. Moreover, to better understand the difference between the influence of HSR and other major transport modes on economic growth, accessibility and connectivity in the highway, air, and water networks are also analyzed.

Main findings of this paper include

1) The analysis confirmed that HSR has a positive impact on economic growth, primarily through improving the accessibility and connectivity in the railway network. We find that the effect of the HSR dummy variable is insignificant, whereas those of accessibility and connectivity are substantial. This implies that the benefit of HSR on economic growth is mainly accomplished by its network spillovers rather than the isolated existence of HSR infrastructure.
2) Between the two location endowment metrics, the effect of accessibility dominates that of connectivity, indicating that economic growth is more sensitive to how fast labor and material can be transported in the railway network.
3) Across various geographic regions and population scale, the GDP of cities in the western region and of medium-sized cities are much more sensitive to accessibility improvements than other city categories; while that of cities in the eastern region and of small cities are much more sensitive to enhanced connectivity.
4) The location endowments of neighboring cities impact the economic growth of one another, reflected by the highly significant spatial autocorrelation effect. Such an effect is found in all transport modes and in most of the subsamples. This implies that proximate cities would benefit from the improvement of each other's location endowments in terms of accessibility and connectivity in transport networks.
5) There is a mismatch between where the largest accessibility improvement occurs and where a percentage improvement generates the largest economic growth. This implies that the extent of economic growth relies on location endowment does not necessarily correlate with the extent of location endowment changes.
6) Compared with other transport modes, the effect of accessibility and connectivity by railway on economic growth is smaller than that by highway, but is larger than those by air and water.

Several important policy implications for China can be obtained from the analysis. Firstly, the analysis sheds light on the potential contribution of HSR on the regional disparity of economic growth. Our empirical results suggest that the GDP of cities in the western region and of medium-sized cities are much more sensitive to accessibility improvements of itself and its neighbors than the other city categorizes; while that of cities in the eastern region and of small cities are much more sensitive to enhanced connectivity. HSR investment can be utilized by the government as a policy tool to narrow down the economic inequalities across regions and four city categorizes.

The second implication is generated from the mismatch between where the largest accessibility improvement occurs and where a percentage improvement generates the largest economic growth. The accessibility improvement by railway tends to have more significant impacts on economic growth for cities in the western region than that in the eastern and central regions, and for medium-sized cities than megacities, small cities, and large cities. It is different with the distribution of the improvement in accessibility, where the maximums occur in the eastern region and megacities respectively in different comparisons. However, where the connectivity increases the most is in line with where unit improvement generates the largest economic growth. This implies that the enhanced connectivity in the railway network should be encouraged in the eastern region, whereas the accessibility improvement might be more effective for the western region to promote economic growth in the future.

The third implication can be derived from the differentiated influence of four transport modes on economic growth. Our empirical study shows that accessibility and connectivity improvement by railway resulted in a smaller increase in economic growth than that of highway, but is larger than those by air and water at national, regional and city levels. The asymmetric impacts of different transport modes should be considered and coordinated in a comprehensive transport system planning, especially for investment choice in the future.

While this study focuses on the positive impact, the rapid development of HSR also generates negative externality such as intensive debt burdens incurred by the expensive construction, operation, and maintenance of HSR systems (Beria et al., 2018; Xu et al., 2019). It is suggested that Railway China needs to consider both the economic growth in the short run and the financial debt in the long run. Researchers have verified the importance of feasibility analysis for HSR lines (e.g., Vickerman, 2017). At present, most existing research evaluates the effect of HSR from one aspect of either the financial effect or the economic enabling effect, separately. Very few have considered both sides. In the future, it is necessary to strengthen the study of a comprehensive evaluation model considering not only the positive but also the negative effects.

This study can be fruitfully extended along with a number of avenues. First, while this paper explored differentiated impacts of various transportation modes on economic growth, neither asymmetric effects on different sectors of the economy nor different impacts on the economic growth rate of different transport modes are considered. Both topics deserve a profound study in the future. Second, this paper measures accessibility by travel time, although there are other factors contributing to the generalized travel cost of each travel mode which accounts for monetary travel cost (ticket price) and value of travel time. Future studies are expected to investigate these effects on traveler intercity mode choices and thus the economic growth. This is particularly relevant in the context of HSR development in China, as the high-ticket price may have hindered the feasibility of HSR for traveler groups. Third, this paper regards air service as one mode without considering different business models. Empirical evidence suggested that HSR and low-cost carriers (LCC) are highly competitive in a certain market (e.g., Wang et al., 2018). It is of interest to examine the interaction between HSR and LCC and their mixed economic impact in future work. Moreover, a future study may also examine the impacts of HSR and its connection with urban transport systems in a multi-modal context

(Zhang et al., 2014a; Wang et al., 2017b; Zhang and Liu, 2019).

CRediT authorship contribution statement

Jingjuan Jiao: Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Project administration, Funding acquisition. **Jiaoe Wang:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Fangni Zhang:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - review & editing, Project administration. **Fengjun Jin:** Conceptualization, Methodology, Funding acquisition. **Wei Liu:** Methodology, Funding acquisition, Writing - review & editing.

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Appendix A. Selection of the spatial econometric model

Three widely used spatial econometric models are introduced in Section 2.1 to examine the spatial autocorrelation, namely spatial Durbin model (SDM), spatial lag model (SLM) and spatial error model (SEM). The models have different physical meanings and economic implications. Several specification tests are conducted to select the appropriate model specification among the SDM, SEM, and SLM.

First, a likelihood ratio (LR) test is implemented to examine the joint significance of spatial and/or time period effects based on an OLS regression, which determines whether spatial fixed effects, temporal fixed effects, or both are included in the spatial model estimations (see Table A.1). In addition, a phi parameter was estimated to test the random effects model against the fixed effect model. If phi is not different from zero, this suggests that a fixed effect model fits the data better, while the value of phi equating one indicates that the random effect model is more appropriate. According to the initial regression results presented in Table A.1, the null hypothesis of the LR spatial fixed test for joint significance is rejected, which indicates that the spatial fixed effect should be included in the model. The LR time period fixed effect test is not rejected, indicating that the time period fixed effect should not be included in the model. Thus, in the following analysis, the spatial fixed effects model is employed to explore the impacts of HSR on economic growth.

Table A.1
Estimation results of panel data without spatial interaction effects

	Pooled OLS (1)	Spatial fixed	Time period	Spatial and time
		Effects (2)	fixed effects (3)	period fixed effects (4)
Intercept	1.030***			
log(FI)	0.188***	0.023***	0.193***	0.009***
Log (E)	0.584***	0.017***	0.569***	−0.018**
HSR Dummy (HSR)	0.190***	−0.024	0.182***	−0.011
log (RA)	−1.082***	−1.238***	−1.726***	0.322***
log(HA)	−1.403***	−2.544***	−2.025***	−0.873***
log(AA)	−0.017	0.005	−0.023**	0.011***
log(WA)	−0.034***	−0.107	−0.021**	22.42
log(RC)	0.022***	0.002***	0.020***	0
log(HC)	0.127***	0.074***	0.124***	0.015**
log(AC)	0.011***	0.003***	0.011***	−0.001**
log(WC)	0	0.003	0	0.003**
LM spatial lag test	6.219**	1484.09***	332.44	753.505***
LM spatial error test	7.408***	2140.72***	852.696***	721.66***
LR spatial fixed effect test	10715.22***			
LR time period fixed effect test	1957.61			

Note: Significance level: ***<0.01, **<0.1.

Second, a Lagrange Multiplier (LM) test (Burridge, 1980) is conducted to identify whether spatial lag dependence or spatial error dependence exists in the wider spatial economic impacts of HSR, and a Wald test is implemented to examine whether the SDM can be simplified to an SLM or SEM (Elhorst, 2010; LeSage and Pace, 2009). The Wald test can be verified by the coefficients associated with the spatial lags of the dependent variable (ρ), the independent variables (θ), and the residual (γ), respectively. The SLM should be chosen if $\rho \neq 0$ and $\theta = \gamma = 0$. The SEM should be chosen if $\rho = \theta = 0$ and $\gamma \neq 0$. The SDM should be chosen over the SLM and SEM if both the hypotheses $H_0 : \theta = 0$ and $H_1 : \theta + \rho\gamma = 0$ are rejected. In case that the Wald test result contradicts the LM test, the SDM should still be adopted since it is a more general framework (Elhorst, 2010).

According to the SDM estimation results shown in Table B.1, the coefficients ρ *and* θ in SDM and γ in SEM are significantly different from zero, namely both the hypotheses H_0 and H_1 are rejected. The LM tests, including the spatial lag test and spatial error test, are all significant for the spatial fixed effects (as shown in Table A.1), also indicating that the spatial lag dependence or spatial error dependence both exist. This implies that the neighboring effects of the economic growth, transport location and the other explanatory variables all prevail in the data. Therefore, the SDM specified in Eq. (2) is chosen to further explore the economic impacts of HSR concerning the spatial autocorrelation effects.

Appendix B. Robustness of the spatial econometric model

Several statistical tests are conducted to examine the robustness of the selected Spatial Durbin Model (SDM). Firstly, we adopted Instrumental Variables (IVs) attempting to deal with the potential endogeneity problems and conducted the Hausman specification test and Davidson-MacKinnon test. In principle, the Hausman specification test can help examine potential endogeneity in the model by comparing the estimation results with and without IVs. If the estimations are not significantly different, this means the use of IVs is not necessary. To do the Hausman test, we should firstly choose instrument variables. To address the issue of endogenous route placement, the transportation literature commonly employs historical information as the IV (Gao et al., 2019). Following this method, the lag variable of each explanatory variable (Zheng and Kahn, 2013), one kind of historical information, is chosen as the IVs in our study. We have tried lag variables for one year, two years, and three years. According to the Sargan test of overidentifying restrictions (a test that helps judge whether IVs and their corresponding variables are endogenous), we find that the accessibility by railway is an endogenous variable, and its IV, one-year lag variable or two-year lag variable, is exogenous. There is little difference in the estimation results with one-year lag variables as IVs and that with two-year lag variables. Therefore, in our paper, we choose the one-year lag variables as the IVs to do the Hausman test. By comparing the results with IVs (calculated using two stage least square estimation) and without IVs (calculated using OLS estimator), we find that there is little difference. Moreover, we conduct the Davidson-MacKinnon test, which can help examine whether the potential endogeneity has a large influence on the estimated results of OLS. According to the Davidson-MacKinnon test result (p-value greater than 0.05), the potential endogeneity has little influence on the estimated results of OLS. These results suggest that we can use OLS to estimate SDM.

Secondly, to re-verify the robustness of an OLS-based SDM, the SDM estimation result is compared with that of the spatial panel autoregressive generalized method of moments (SPGMM). The SPGMM method is built upon the generalized method of moments (GMM). It is commonly acknowledged that the GMM can be used to examine the potential endogeneity problem caused by lag variables; similarly, the SPGMM can be used to test this problem for SDM using panel data. Specifically, if there is no significant difference between the results of SDM and SPGMM, SDM is robust to estimate the impacts of HSR on economic growth. Following the method of Shehata (2013), we estimate the SPGMM and present the results in Table B.1. By comparing the results of SDM and SPGMM, the two sets of coefficients are generally consistent. This indicates that the estimation results of SDM based on OLS are robust to explain the economic impacts of HSR in China.

Table B.1

Estimation of HSR's impacts on economic growth using SDM with fixed effect and SPGMM

	SPGMM	SDM		SEM
		Independent variables	Spatial lag	
Intercept	4.2918***	–	–	–
log(FI)	0.1024***	0.1***	0.02***	0.247**
Log (E)	0.4048***	0.201***	0.038***	0.091**
HSR Dummy (HSR)	0.0092	−0.026	0.005	0.004
log (RA)	−1.2369***	−1.232***	0.181***	−1.395***
log(HA)	−1.8863***	−1.726***	0.163***	−1.889***
log(AA)	0.0129	0.014	0	0.001
log(WA)	0.1731	0.221	0.05	0.06
log(RC)	0.011***	0.001**	0.001	0.021**
log(HC)	0.0221***	0.028***	0.005	0.071***
log(AC)	0.0090***	0.001***	0.001**	0.001*
log(WC)	0.0045***	0.002***	0	0
GDP	–	–	0.693***	–
W*ε	–	–	–	0.636**
R^2	0.7321	0.992		0.987
Log-likelihood	−1852.9889	2997.1918		2923.28

Notes: 1. *** signifies that the test is significant at the 0.1% level.

Thirdly, we use the panel Granger causality test to check the mutual causal relationship between locational advantage in the railway network and economic growth. Before doing the Granger causality Wald test, the panel unit root test (LLC and IPS tests) method and the panel co-integration test (Kao, Pedromi and Johansen tests) method are employed. The results of the panel unit root test indicate that the panel is not stable, but that of the panel co-integration test shows that there is a co-integration relationship for the panel data of WATT, WDC, and GDP. The results of the panel Granger causality test indicate that there might be a bidirectional causal relationship between accessibility and economic growth; but that between enhanced connectivity and economic growth is unidirectional, as shown in Table B.2. Having said that, according to the results Davidson-MacKinnon test, the potential endogeneity has little influence on the estimated results of OLS (please refer to our response to R1.4 for details). Therefore, the estimation results are robust to the potential endogeneity.

Table B.2

Results of panel Granger causality Wald test

Null hypothesis	Chi-square statistic
lnRC does not Granger Cause lnGDP	13.7***
lnGDP does not Granger Cause lnRC	0.635
lnRA does not Granger Cause lnGDP	12.365***
lnGDP does not Granger Cause lnRA	16.39***

Notes: 1. *** signifies that the test is significant at the 0.1% level.

2. RA: accessibility in the railway network; RC: weighted degree centrality in the passenger train network; chi2 statistic: Chi-square value of Wald Test.

Appendix C. Robustness of the coefficient value in the connectivity measurement

Table C.1
Estimation results with varying α values in WDC for SDM model (with reference to Table 6)

a	0.0	0.1	0.3	0.5	0.7	0.9	1.0
RC	0.0006**	0.0006**	0.0006**	0.0006**	0.0007**	0.0007**	0.0007**
W*RC	0.0012	0.0012	0.0012	0.0013	0.0013	0.0014	0.0014

Note: 1. ** signifies that the test is significant at the 1% level.

2. RC: weighted degree centrality in the passenger train network; W*RC: the spatial lag of weighted degree centrality in the passenger train network.

Appendix D. Spatial distribution of the accessibility improvement by three transport modes during 2007–2015

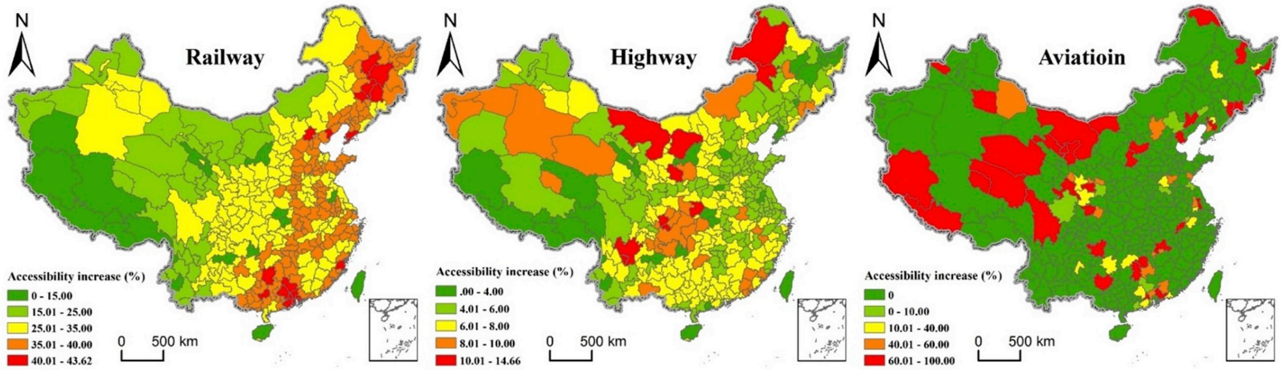

Fig. 3. Improvement in accessibility by three transport modes during 2007–2015. Note: Since there was little change in the spatial patterns of water ports during 2007–2015, the improvement in accessibility of all cities is zero and thus is omitted in Fig. 3.

Appendix E. Spatial distribution of the connectivity improvement by three transport modes during 2007–2015

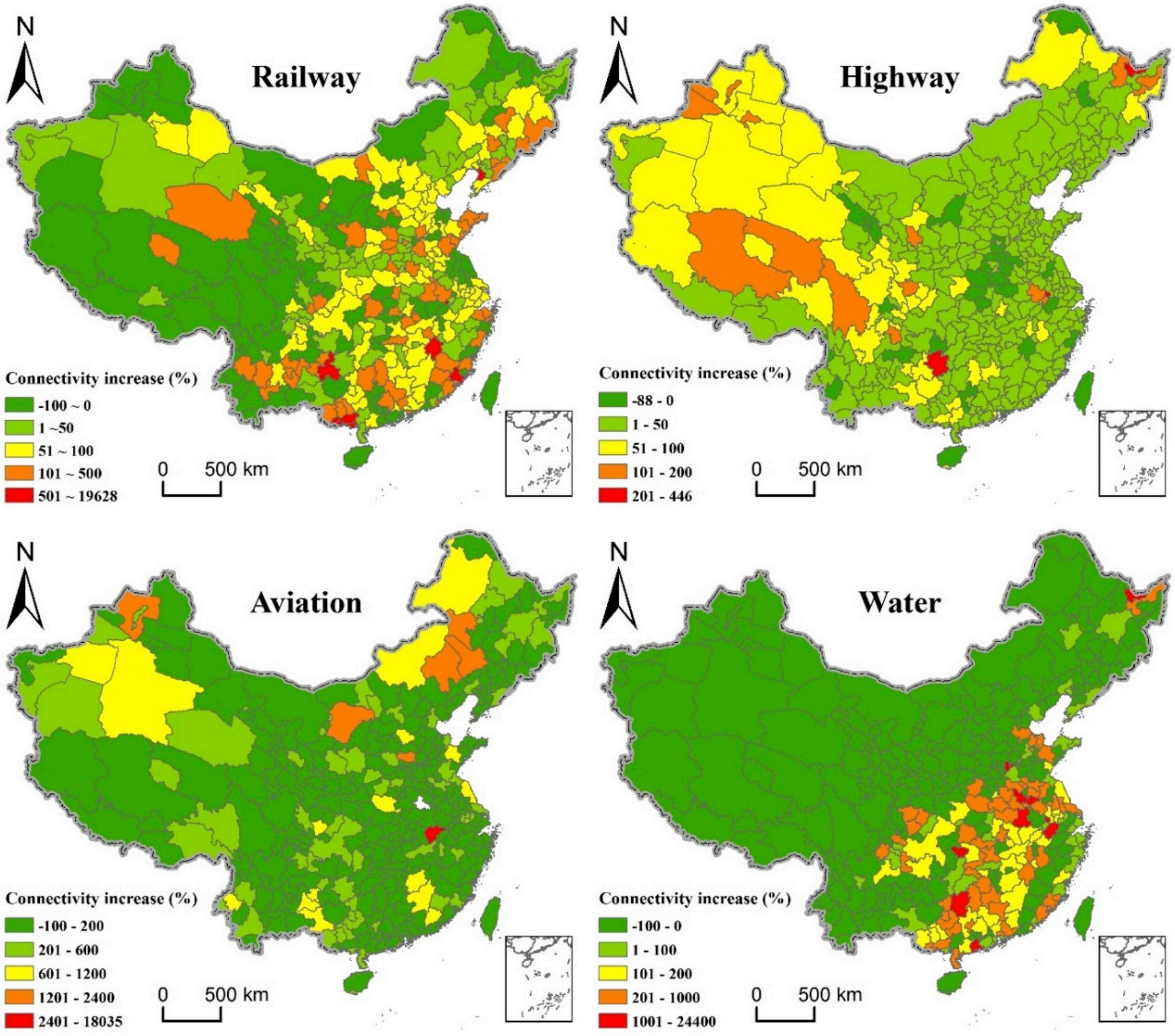

Fig. 4. Improvement in connectivity by four transport modes during 2007–2015.

Appendix F. Abbreviation table

Term	Abbreviation
High-speed railway	HSR
Gross domestic product	GDP
Weighted average travel time	WATT
Weighted degree centrality	WDC
Low-cost carriers	LCC
Ordinary Least Square	OLS
Spatial Durbin model	SDM
Spatial panel autoregressive generalized method of moments	SPGMM

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