Cities 105 (2020) 102845

Contents lists available at ScienceDirect

Cities

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

Dynamic network coupling between high-speed rail development and urban growth in emerging economies: Evidence from China

Ying Guo, Biao Li, Yilong Han*

School of Economics and Management, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
High-speed railway
Network
Urban economic growth
Urban agglomeration
Coupling relationship
Emerging economy

ABSTRACT

Developing new types of transportation is considered a key solution to meet the extreme demands placed on traditional transportation infrastructure due to the increasing flow of production factors for national urban growth, especially in emerging economies. Both city transportation networks and city economic networks reflect intercity relationships in urban systems from different aspects. Although HSR networks are being developed rapidly worldwide, we still lack a deep understanding on how HSR relates to the economic growth of urban agglomerations from a "double-network" perspective. In this research, we first built city HSR networks and city economic networks, respectively, before the QAP method was used to examine their relationship during 2010–2015. By analyzing comparatively the differences of the coupling relationship in various areas in China as a typical case, this study contributes to the understanding of the dynamic coupling relationship between new forms of transportation and regional economic development. We found a strong coupling relationship between HSR and economic growth, and HSR tends to play a more prominent role in promoting urban integration and development in areas with more developed economies (coefficients of more developed areas are all above 0.6, while that of less developed areas are below 0.4). Such correlated relationship is more obvious in smaller administrative scopes compared to cross-administrative regions. This study proposed a research framework for "double-network" analysis in exploring the relationship between the different networks. It could also provide policy implantation for balanced regional development in emerging economies.

1. Introduction

Megaprojects have become a worldwide prevailing phenomenon along with rapid urbanization (Flyvbjerg, 2014). Specifically, large-scale transportation infrastructures, such as roads and railways, are widely regarded as an engine of economic growth that reduces travel time and expenditure, attracts investment, and creates new jobs (Hong, Chu, & Wang, 2011). The ever-increasing flow of production factors has placed high demands on transportation systems, especially in emerging economies (Ali, 2012). The congestion of conventional transportation systems, e.g., roads and railways, is intensifying and fails to meet the needs of fast-growing economic development. To address this issue, development of new transportation systems has been suggested as a critical solution (Ali, 2012).

High-speed rail (HSR) has been considered one of the most significant technological breakthroughs in transportation systems (Campos & de Rus, 2009), exerting huge influences on economics, accessibility, and population flows (Chang & Lee, 2008). Since HSR has achieved considerable success and led to positive outcomes in developed regions such as Japan and western Europe, this transportation technology is expected to provide possibilities for balanced and sustainable development in emerging economies (Verma, Sudhira, Rathi, King, & Dash, 2013). However, huge differences exist in economic conditions, social structures, as well as national policies between developed regions and emerging economies. Since the construction of new forms of transportation consumes significant economic and social capitals, investment decisions could be more controversial in emerging economies (C. Chen & Vickerman, 2017). Their dysfunction could further result in negative environmental risks or waste (Chester & Horvath, 2010). Thus, it is of great importance to study this new form of transportation under the specific context of emerging economies.

Advancement of transportation infrastructures accelerates flows of production factors and stimulates the development of regional economy to a certain extent, while rapid urban sprawl reinforces the need for improved transportation infrastructure in turn. Therefore, coupling relationship (interaction relationship) exists between urban economic growth and transportation infrastructure development. Transportation networks and economic networks not only contribute to the integration

* Corresponding author.
E-mail addresses: gracee112@tongji.edu.cn (Y. Guo), leebiao_tju@sina.com (B. Li), yilong.han@tongji.edu.cn (Y. Han).

https://doi.org/10.1016/j.cities.2020.102845
Received 9 August 2019; Received in revised form 10 March 2020; Accepted 13 June 2020

of geographically dispersed cities in urban areas, but also help understand the formation and reconstruction of urban hierarchy structure from different aspects. Further, economics and transportation infrastructures are both evolving over time, and a dynamic insight could better reveal the trends of the interaction relationships and the process of coupling development. Therefore, the dynamic interrelationship, or the connection and interaction, between urban transportation networks and urban economic networks from a double-network comparative perspective is worth exploring. China is widely recognized as one of the fastest growing economies over the past few decades, and Chinese HSR has developed at an unprecedented speed since 2008. The magnitude and scale of Chinese HSR and China's vast territory provide an ideal setting for cross-regional analysis and comparison since the impacts of the transportation infrastructure on economy vary at different geographical regions. In this study, we chose China as a typical example to explore the dynamic network-coupling relationship between new forms of transportation and urban growth.

2. Literature review

As the inter-connections between cities become more complex, research in urban systems has gradually evolved from analyzing city attributes to examining intercity relationships under a network context, namely urban network research (Camagni & Salone, 1993). The level of development of a city should be described not only by econimic quantitative indexes, but also by its relationships with other cities, as it implies how well this city is connected in the urban system (Taylor, Walker, Catalano, & Hoyler, 2002). With the development of graph theory and social network analysis method, the study of interrelationships between cities under the network context has become a prevailing issue in the field of urban geography and regional economics.

2.1. City economic network

The complex network theory offers a mathematical foundation for urban systems studies. In the context of network, research on spatial interaction and economic connections within city systems mainly include two aspects, namely city economic network (cooperation relations based on economic activities and knowledge exchange flows) and city transportation network (spatial linkages based on infrastructure systems such as railway networks, road networks and aviation networks). In the research of city economic network, inter-firm relations are often considered a measurement of economic linkages. The position of cities in the global economy depends on the structure of relationship networks, which are constantly constructed and restructured by the power and influence of corporate actors and the industries that define them (Taylor et al., 2002). For example, van Oort, Burger, and Raspe (2010) employed data on inter-firm relations to examine urban integration and economic complementarities in the Dutch Randstad. Sigler and Martinus (2017) collected information from 1840 corporations and built four economic networks of material, energy, industrial, and finance, respectively, before the differences and structural similarities were analyzed between cities under different economic sectors.

However, since it is difficult to acquire accurate empirical data on economic activities such as trade flows and the commuting population between cities, theoretical modeling is often used as an alternative to quantify the economic connections. GDP and population have been regarded as irreplaceable indicators of urban economic competitiveness (Lin & Song, 2002), and they are often selected as basic indicators in theoretical models. For example, Sun, Tang, and Tang (2015) studied the economic network structure of the urban agglomeration in the middle reaches of the Yangtze River in China using GDP and population indexes. Jung, Wang, and Stanley (2008) measured South Korean economic relations by modeling on population and distance between cities. Similar studies evaluating economic relations through theoretical model also include international trades (Carrère, 2006) and tourism (Morley, Rosselló, & Santana-Gallego, 2014). As most prior studies were static analysis for a specific year or period, we found that there was a lack of research on the spatiotemporal evolution of economic linkage networks, neglecting the fact that economic relations between cities are changing dynamically. By adding time-related attributes to economic networks, the evolution path of the networks could be determined beyond a single time moment approach (Schweitzer et al., 2009).

2.2. City transportation network

Since transportation infrastructures provide physical channels to transport goods and human resources, the inherent network characteristics of the transportation network adds greater complexity to the regional development. City transportation networks, constructed on infrastructure systems, illustrate the significant role of transportation infrastructure in urban systems, represented by road networks (Zhao, Yu, Wang, & Kan, 2017), aviation networks (Ma & Timberlake, 2008; Wang, Mo, Wang, & Jin, 2011) and railway networks (Hou & Li, 2011; Wang, Jin, Mo, & Wang, 2009; Wanke, Chen, Liu, Antunes, & Azad, 2018).

When conventional transportation systems (e.g. roads and railways) lag behind the growing demand for rapid flow of production factors, congestion problems occurred and seriously impeded economic growth (Ali, 2012). As a form of emerging transportation infrastructure, the HSR network has expanded rapidly worldwide and brought two changes to the urban system. First, HSR linkages between cities were generally considered as an optimal measurement to reflect urban hierarchical structures in city transportation networks. Research on topological properties and city positions in HSR networks provided a new perspective that helped to understand the evolution of structural and spatial properties of urban system at a national/regional level (Verma et al., 2013; Jiao, Wang, & Jin, 2017; Cao, Feng, & Zhang, 2019). For example, Wang and Duan (2018) summarized seven types of winner and loser cities in terms of population distribution under the development of HSR network in Yangtze River Delta, China. Second, the efficiency and spatial impacts of HSR on urban system were also manifested in its relationship with space-economy development (Chen, 2012). Quantification of the economic performance of HSR, such as accessibility gains and time-space shrinkage (Cao, Liu, Wang, & Li, 2013; Shaw, Fang, Lu, & Tao, 2014), became a prevailing means in exploring the relationship between HSR network and regional economic growth. For instance, Cheng, Loo, and Vickerman (2015) researched on the effects of Spanish HSR network efficiency and spatial equality impact on spatial-economic distribution through network diffusion. Li, Huang, Li, and Zhang (2016) studied the accessibility gains of HSR network on the distribution of urban economic activities, while Deng, Wang, Yang, and Yang (2019) revealed that HSR did not always yield growth opportunities, as it could bring serious challenges to the cities encountering population declines. Although a number of prior studies led to some reliable findings, they mostly employed regression models to study the cases before and after the opening of HSR to highlight its unilateral effect on the economic performance; the important network attributes that both HSR and urban economic development exhibited were largely neglected (Guirao, Campa, & Casado-Sanz, 2018; Li et al., 2016; Xu & Huang, 2019).

2.3. Relations between city economic and transportation network

Prior research mostly focused on the network characteristics and spatial effects of individual HSR networks or urban economic networks within a certain region. There is a lack of in-depth comparative analysis that considers both of the networks, except Mahutga, Ma, Smith, and Timberlake (2010) conducted a comparative study between world city system gauged by international flight flows and world system based on international trade flows, and Lao, Zhang, Shen, and Skitmore (2016) compared Chinese aviation network and city economic network.

However, both of the abovementioned studies only researched on the similarities and differences of network structural and city hierarchy by analyzing basic centrality indicators of cities in urban systems, without considering the network relationship as a whole. To fill the gap, this paper provides a new perspective to study the dynamic coupling relationship between city transportation and economic network. As the city transportation networks and the economic networks respectively reflect the structural characteristics of urban system and city spatial interaction from different levels, it is of great necessity to explore the dynamic coupling relationship between them from a double-network perspective. Moreover, the coupling analysis approach at the network level proposed in this study could provide empirical evidences and theoretical basis for city network research.

3. Methodology

In this study, we first constructed and analyzed HSR networks considering cities as network nodes and HSR daily service frequency as network edges. Then, based on the gravity values calculated as network edges, we built economic networks and further classified their spatial patterns. Last, a comparative analysis was conducted to explore the dynamic coupling relationships between city HSR networks and economic networks. The research framework of this study is illustrated as a three-step approach in Fig. 1. Details about case settings and each steps were elaborated in the following subsections.

3.1. Case settings

To better explore the evolution characteristics of the HSR network and its relationship to regional economic development, we selected five representative urban agglomerations in China as studied cases considering economic development, HSR density, and population size. They are the Yangtze River Delta (YRD) urban agglomeration, the Pearl River Delta (PRD) urban agglomeration, the Beijing–Tianjin–Hebei (BTH) urban agglomeration, the Central Plains (CP) urban agglomeration, and the Yangtze River Middle Reaches (YRMR) urban agglomeration, comprising a total number of three municipalities and 65 prefecture-level cities across 11 major provinces (Table 1). The selected cases could be considered the epitome of China's recent development for spatial-temporal analysis (Fig. 2).

3.2. HSR network analysis

Nodes and links are two main attributes of a network. For the building of HSR networks, cities are considered as network nodes while the HSR transits between cities are network links. Here, we adopted a weighted undirected network-modeling approach. In other words, HSR daily service frequencies were regarded as network linkages without considering linkage directions. HSR data from 2008 to 2015 were acquired from the National Railway Administration of China (http://www.12306.cn) after the HSR network was established, the social network analysis (SNA) was applied to analyze the network characteristics.

Social network analysis (SNA) is a quantitative method of analyzing network structure. Network density and degree centrality were chosen to study the evolutionary characteristics of HSR networks. Network density represents the close relationship between nodes in a network, where m indicates the actual number of connections in the network (HSR links between cities) and n refers to the total number of nodes (cities with HSR stations in this paper). A higher density value means a stronger connection between actors.

$$Density = \frac{2m}{n \times (n-1)} \tag{1}$$

Considering the influence of node degrees and connection weights, we implemented a weighted degree centrality index (W_D) to analyze HSR networks, as in the equation:

$$W_{D(i)} = \left(\sum_{j}^{n} x_{ij}\right)^{1-\alpha} \times \left(\sum_{j}^{n} w_{ij}\right)^{\alpha} \tag{2}$$

where x_{ij} is a binary value, if there exist HSR links between city nodes, then $x_{ij} = 1$. w_{ij} denotes the weight of links between node i and node j (daily service frequency between two city nodes). Consuming the centrality and weighted centrality has equivalent effects on city nodes, the adjustment parameter α is set as 0.5 in our study (Opsahl, Agneessens, & Skvoretz, 2010). In this study, related network indicators were calculated using the UCINET software.

3.3. Economic network analysis

Economic networks were established based on the economic relations between cities. Considering the difficulty of economic data acquisition, this study employed a theoretical model of gravity model to measure the economic relationship between cities. Early studies in regional economies demonstrated that rules of economic activities and laws of nature are analogous (Pöyhönen, 1963). Built on Newton's gravity model, researchers developed the city gravity model to evaluate the relationship intensity/strength between two cities (Barthélemy, 2011). The city gravity model has long been recognized for its consistent empirical success in explaining economic activities. Based on the

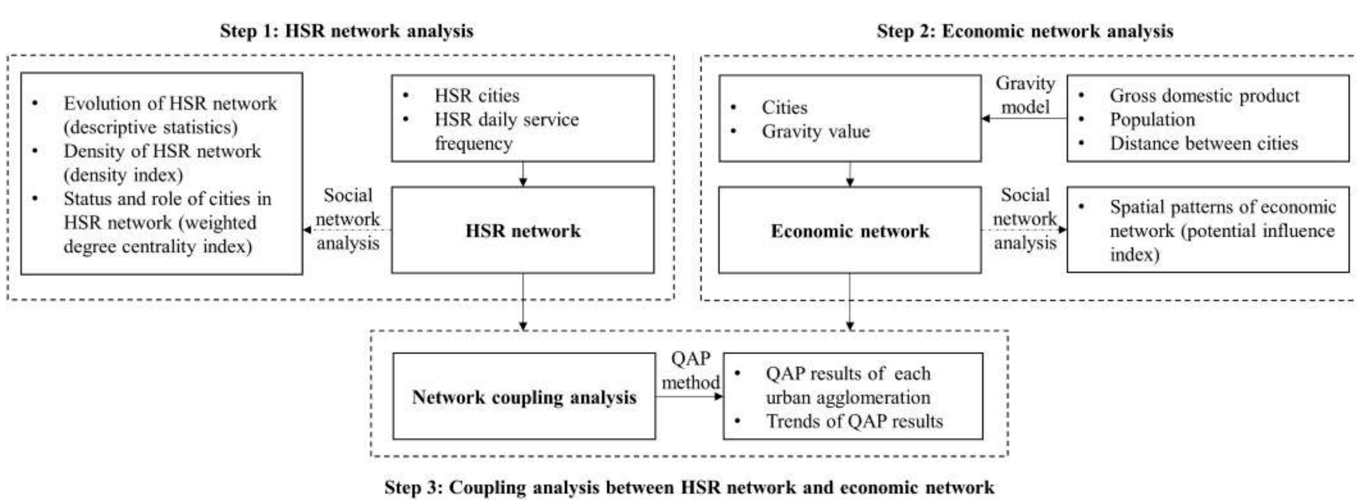

Fig. 1. Research framework.

Table 1
Statistics of five representative urban agglomerations.

Urban agglomeration	Number of cities	GDP (trillion USD)						Permanent population (million)					
		2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015
YRD	16	0.62	0.72	0.81	0.91	1.00	1.08	41.8	42.1	43.2	46.0	47.1	48.0
PRD	9	0.43	0.50	0.54	0.61	0.67	0.74	19.0	19.2	19.5	20.6	21.0	23.8
BTH	8	0.39	0.46	0.51	0.55	0.61	0.68	28.7	29.1	29.4	29.5	31.7	36.8
CP	17	0.09	0.11	0.13	0.15	0.16	0.17	21.1	21.7	22.7	22.0	22.8	20.9
YRMR	18	0.20	0.25	0.28	0.32	0.35	0.38	22.0	22.7	22.9	22.8	23.4	23.9

Note. YRD = Yangtze River Delta urban agglomeration, PRD = Pearl River Delta urban agglomeration, BTH = Beijing–Tianjin–Hebei urban agglomeration, CP = Central Plains urban agglomeration, YRMR = Yangtze River Middle Reaches urban agglomeration.

simplified gravity model, the spatial association between two cities is proportional to city quality (Q_i and Q_j) and inversely proportional to geographical distance between them (d_{ij}),

$$F_{ij} = k\frac{Q_i Q_j}{d_{ij}^b} \tag{3}$$

where k is an empirical constant, and b is the distance-attenuation coefficient, both of which can be obtained by multivariate statistical methods. Taaffe (1962) pointed out that the b value that best describes aviation flows is changing but close to 2. Krings, Calabrese, Ratti, and Blondel (2009) verified that b equals to 2 when studying telecommunications between cities, and similarly, Jung et al. (2008) identified that Korean highway traffic flows formed a gravity model proportional to population size with $k = 1$, $b = 2$. Therefore, we adopted the same empirical constant and distance attenuation coefficient in this study, consistent with prior research under similar study contexts (Jung et al., 2008; Wang, Deng, Sun, & Song, 2014). Since population and GDP are often considered as important measurement of urban growth (Abhishek, Jenamani, & Mahanty, 2017), in this paper we calculated the parameter Q by the product of GDP and the permanent population in municipal districts after data normalization (Hou, Liu, & Yue, 2009; Lao et al., 2016). The economic data, such as regional population and GDP, were collected from the China Economic Internet Statistics Database (http://db.cei.cn).

After the economic networks were established, considering that there are various gravitational relationships between each of the two cities, this paper adopts an approach that connects a city with a nearby city within the studied urban agglomerations which exhibits the strongest gravitational relationship to define the structure of urban systems (Miao & Zhou, 2017). This process proceeds as follows,

$$G_m^{max} = \max(G_{m1}, G_{m2},..., G_{mn}) \tag{4}$$

where ${G_m}^{max}$ refers to the largest gravity value between city m and a nearby city in the urban agglomerations, and G_{mn} refers to the gravity value calculated by gravity model between nodes m and n. To explore the hierarchical structure of cities in the economic networks, potential influence of a city based on the degree centrality index was applied, as follows, for further analysis,

$$G_i^p = \sum_{m=1}^{n} G_m^{max}(i) \tag{5}$$

where G_i^p refers to the potential influence of city i and ${G_m}^{max}(i)$ refers to the largest gravity value that links to node i.

3.4. Coupling analysis between HSR network and economic network

A coupling analysis was conducted after two networks were built. To do so, Quadratic Assignment Procedure (QAP) that based on multiple matrix permutation was implemented in this study. QAP is a method of comparing corresponding element values in two or more square matrices by taking into account the auto-correlation errors when data are interdependent in social networks (Krackardt, 1987). As a matrix permutation test, QAP compares the observed graphical statistics (correlation or covariance) with the distribution of the same

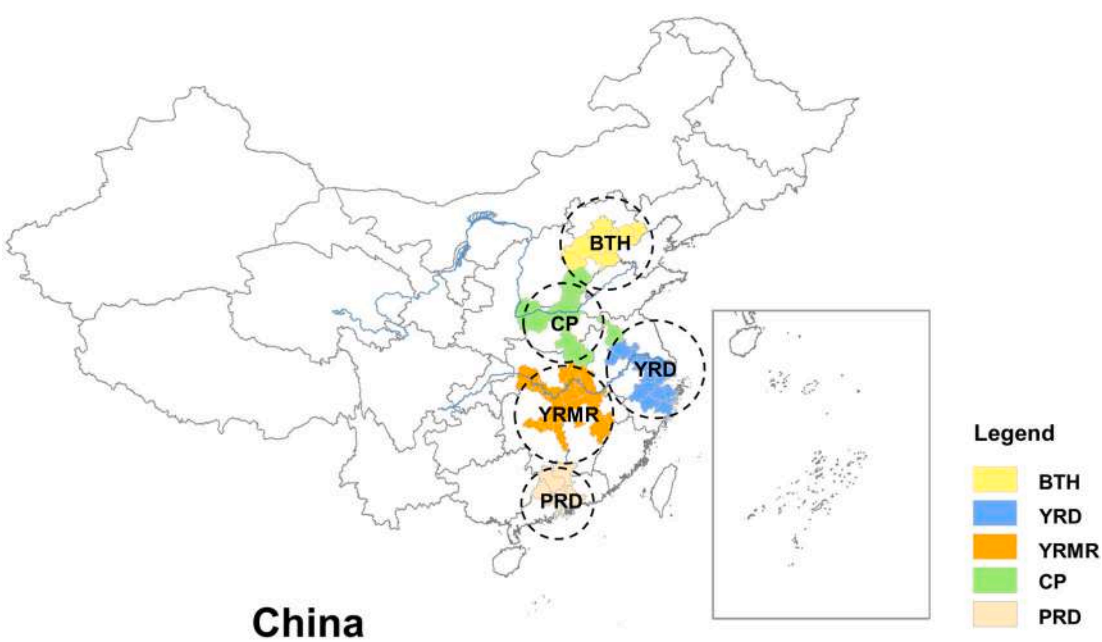

Fig. 2. Five representative urban agglomerations in China.

statistic from simultaneous row and column permutation of the respective adjacency matrix (Butts, 2008). Specifically, QAP permutates the rows and columns of the original matrix multiple times for correlation analysis between the original matrix and the permutated matrices to obtain a reference distribution of all correlation values (Lee, 2019). However, it is not practical to consider all the permutations of the matrix in most situations, because the number of permutated matrices will be very large as the number of nodes in matrix increases. A good approximation of the reference distribution is to take a random 1000 samples from the set of all possible permutated matrices (Lindgren, 2010). QAP is widely used to analyze the relationship between two networks (Rank, 2008), thus was used in this research to examine the relationship between HSR networks and urban gravity networks. The QAP results were calculated by using the UCINET software.

4. Results, findings, and discussions

4.1. Development of HSR networks

China's HSR has developed rapidly, and the number of cities that are connected by high-speed trains has increased from 15 to 175 between 2008 and 2015 as illustrated in Fig. 3. Geographically, the HSR network gradually spread from Beijing, the capital city, and the eastern region to central, western, and northeast areas, forming a complex and nationwide network (Fig. 4). Expanding of HSR lines have greatly improved accessibility between cities. Most cities with better accessibility are provincial capitals (shown in green) and municipalities (shown in red).

Fig. 5 illustrates the fluctuation of HSR-network density (calculated based on Formula 1). As the design layout of HSR lines continued to expand to remote and undeveloped regions, many new nodes of peripheral cities emerged in the HSR network; as a result, the whole network is becoming less dense. The reason for the sudden increase in 2011 was the opening of an HSR line connecting two of China's largest but dispersed cities, closely linking several separate lines as a whole and greatly improving city connections in the eastern and central areas of China.

We selected the top 10 cities in the calculated results of weighted degree centrality in 2011, 2013, and 2015 for comparative analysis (calculated based on Formula 2). The results tabulated in Table 2 indicate that the YRD urban agglomeration plays an important role in China's HSR network, and acts as a vital transportation hub. YRD urban agglomeration is one of the first urban agglomeration listed as national strategic development plans in China, with Shanghai, the largest financial and economic city, as its leading city. The GDP and residential population of YRD urban agglomeration account for 18.5% and 11% of the whole country respectively. Huge potential of commuting population, market development and the extraordinary geographical advantages contribute the YRD region to be the critical transportation hub in China.

Cities with more HSR lines hold a more significant status in the network. For example, the status of Beijing is rising due to the construction of many newly built lines such as the Beijing–Guangzhou line and the Beijing–Harbin line. Also, such development highly relates to the political status of Beijing, the capital of China. In contrast, although Shanghai is the core hub of the YRD region and one of the first cities to operate HSR, its urban status has been declining, with no new routes built since 2011.

Also, the status of traditional railway transportation hubs with slow construction of high-speed rails is being replaced by emerging HSR cities, which is similar to (Jiao et al., 2017). For example, the construction of HSR lines developed relatively slowly in Zhengzhou, a conventional railway hub in China that only has two lines crossing, resulting in a less important status in the urban network. As a result, the centrality indicator of those conventional hub cities is far behind emerging HSR cities, such as Suzhou and Changzhou in the YRD region.

4.2. Economic influence of regional centers

In China, administrative areas consist of provinces and municipalities. China has three types of cities, namely municipalities (directly under the control of the central government), provincial capitals (central cities in the provincial boundaries), and prefecture-level cities (located in the same provincial area as provincial capitals, but less important to their status at the administrative level). Because municipalities and provincial capitals have equivalent status from an administrative perspective, they are classified as first-tier cities in this paper for the convenience of subsequent analysis, whereas prefecture-level

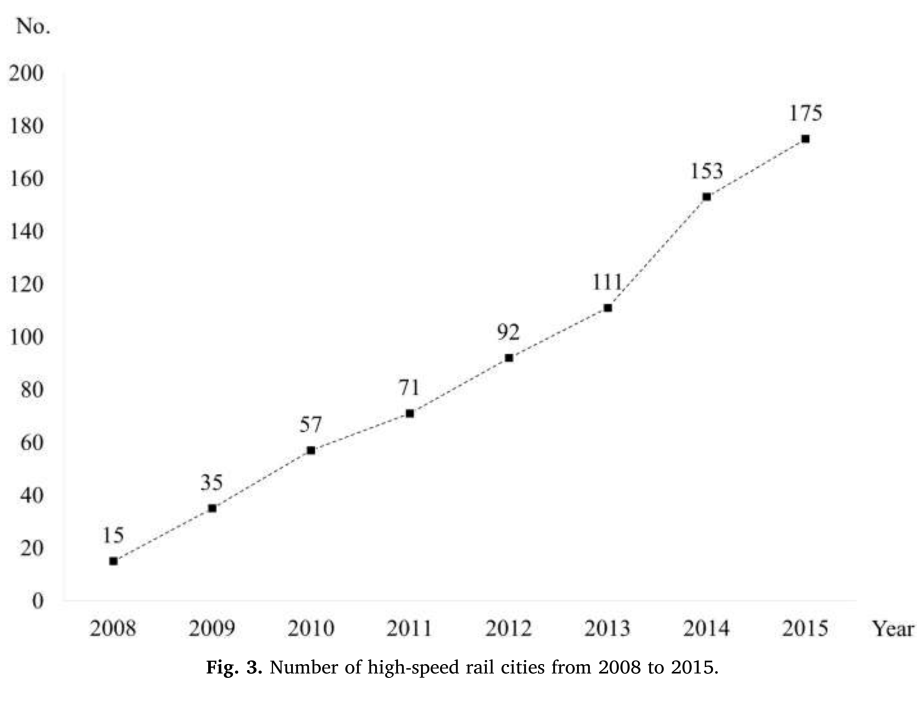

Fig. 3. Number of high-speed rail cities from 2008 to 2015.

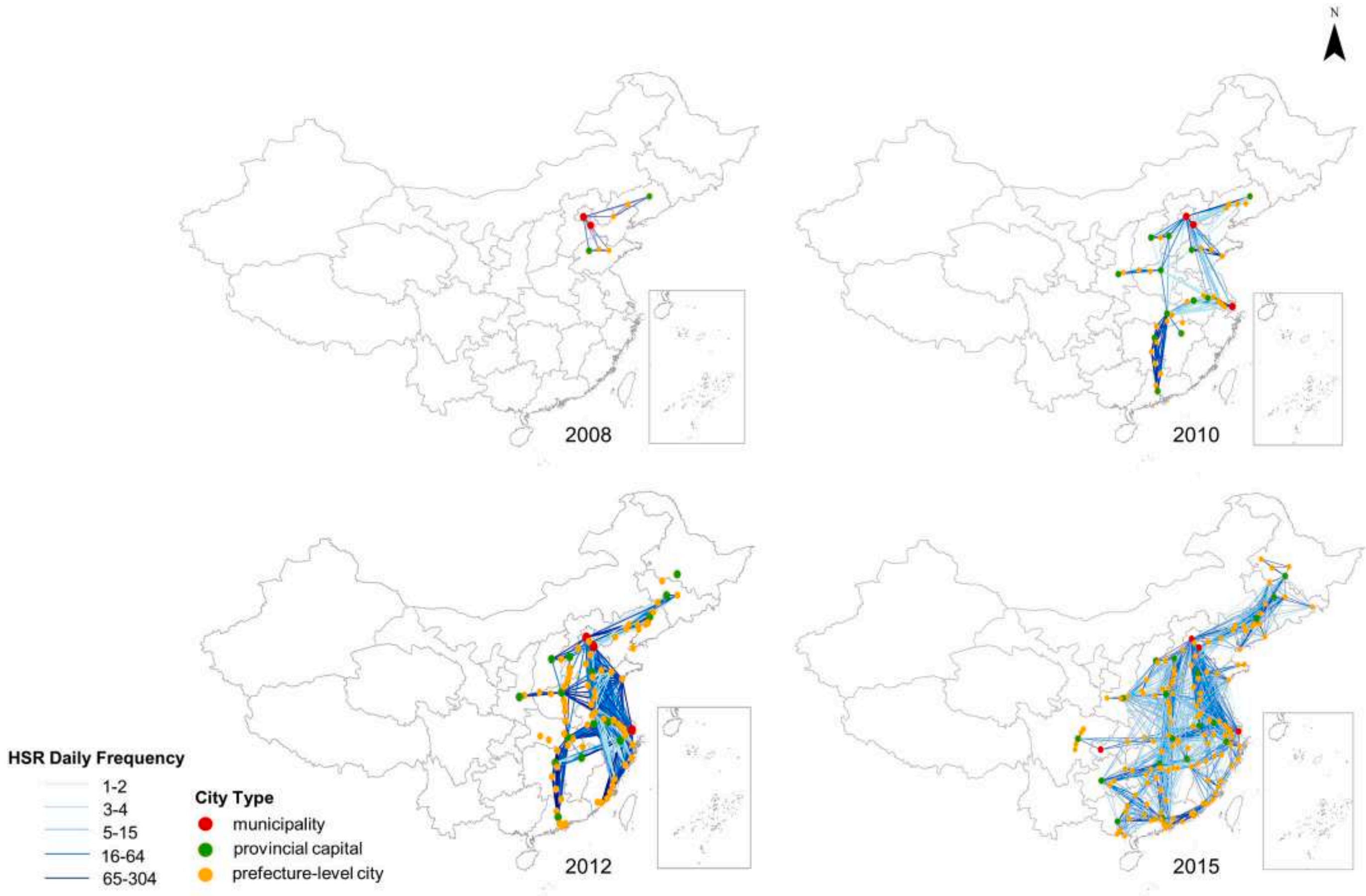

Fig. 4. Evolution of China's high-speed rail network from 2008 to 2015.

cities are second-tier cities. Evolution of gravity values in different urban agglomeration (calculated based on Formulas 3 and 4) are illustrated in Figs. 6–10. Three distinct urban spatial patterns, namely monocentric structure, twin-city structure and polycentric structure, are further categorized (calculated based on Formula 5) and characterized in detail as follows,

4.2.1. *Monocentric structure*

A monocentric structure exists in the region with only one first-tier city, which is often a financial or political center. For instance, Zhengzhou is the only provincial capital in the CP urban agglomeration (Fig. 6). As a result, a radical structure characterizes the spatial concentration of the regional economy; that is, the only core city is the

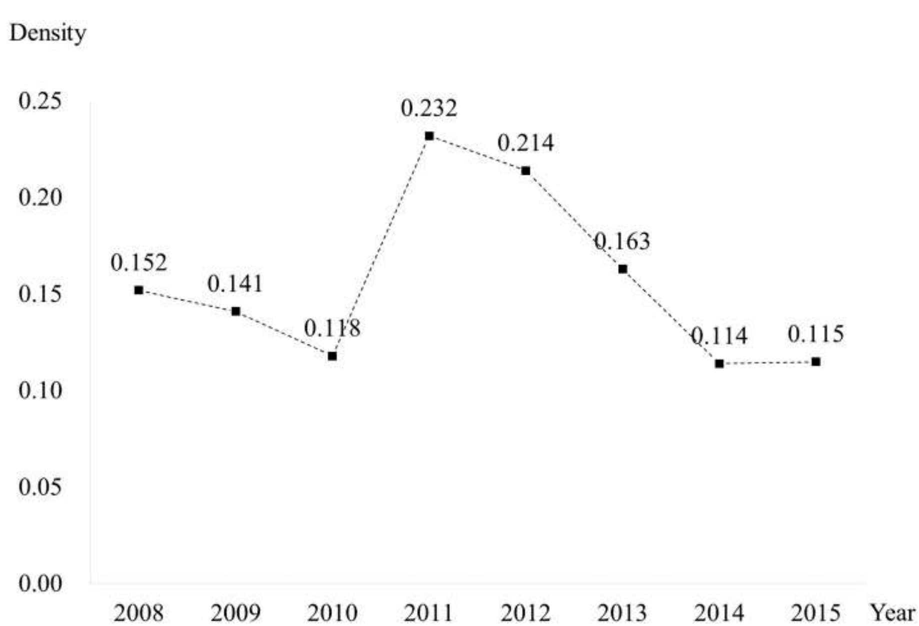

Fig. 5. Density of China's high-speed rail network from 2008 to 2015.

Table 2
Top 10 weighted degree centrality cities.

Rank	2010			2013			2015		
	City	Location	Centrality	City	Location	Centrality	City	Location	Centrality
1	Shanghai	YRD	298.0	Beijing	BTH	304.0	Beijing	BTH	356.5
2	Nanjing	YRD	250.0	Nanjing	YRD	280.0	Guangzhou	PRD	322.9
3	Beijing	BTH	216.7	Shanghai	YRD	253.5	Nanjing	YRD	313.1
4	Wuxi	YRD	212.8	Wuhan	YRMR	236.6	Shanghai	YRD	311.4
5	Suzhou	YRD	212.7	Wuxi	YRD	201.1	Wuhan	YRMR	294.6
6	Changzhou	YRD	190.6	Suzhou	YRD	198.2	Changsha	YRMR	283.0
7	Zhenjiang	YRD	178.5	Changzhou	YRD	191.1	Jinan	–	217.6
8	Jinan	–	175.5	Jinan	–	175.7	Suzhou	YRD	210.5
9	Hangzhou	YRD	165.5	Zhengzhou	CP	174.7	Changzhou	YRD	208.2
10	Xuzhou	YRD	139.1	Changsha	YRMR	171.5	Hangzhou	YRD	207.4

Note. YRD = Yangtze River Delta urban agglomeration, PRD = Pearl River Delta urban agglomeration, BTH = Beijing–Tianjin–Hebei urban agglomeration, CP = Central Plains urban agglomeration, YRMR = Yangtze River Middle Reaches urban agglomeration.

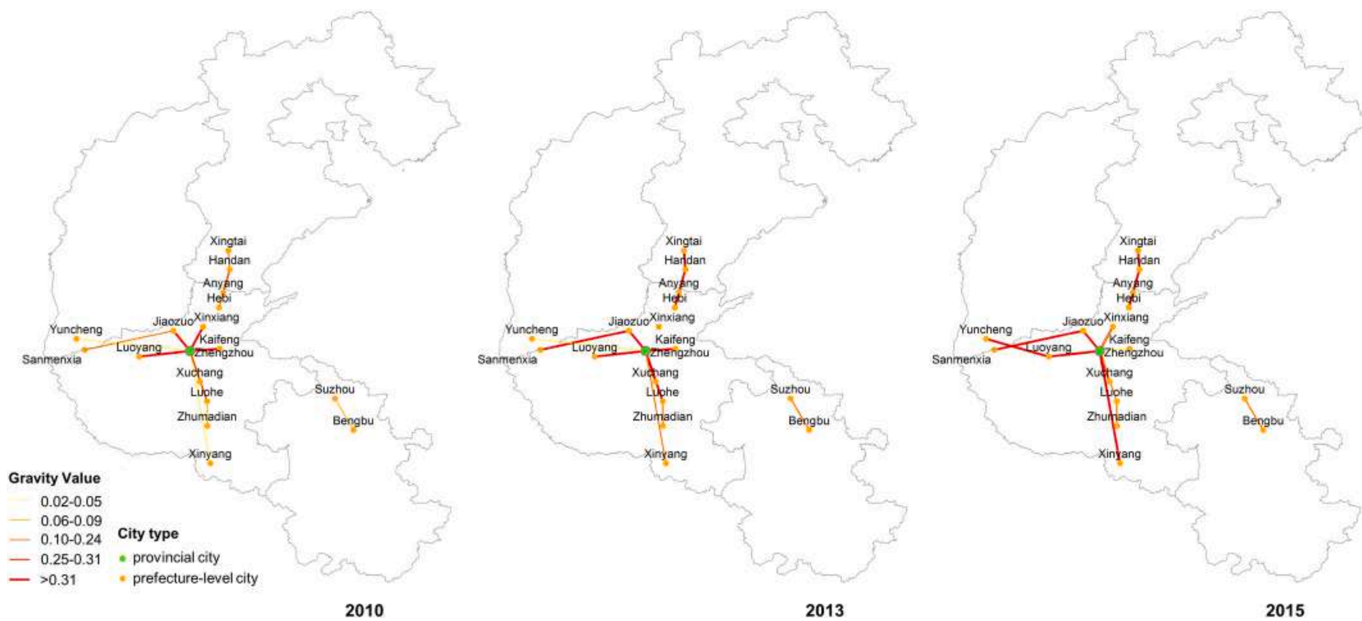

Fig. 6. Evolution of gravity values in the Central Plains urban agglomeration.

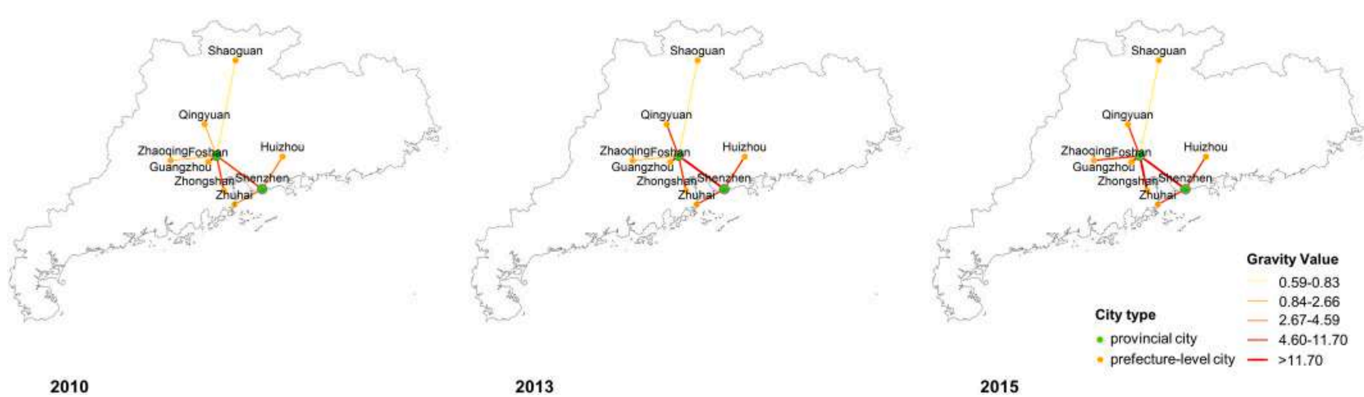

Fig. 7. Evolution of gravity values in the Pearl River Delta urban agglomeration.

economic growth pole. The core city in this structure is not only the hub of conventional transportation systems, but also the intersection of new transportation lines. Monocentric structures mostly occurred before the development of HSR, but the additional flow-increasing effects of HSR reinforced this structure. The radiation capacity of Zhengzhou has been enhancing over time, and its significant status has been strengthened consistently, similar to Paris, a typical city with radial network type (Perl & Goetz, 2015).

4.2.2. *Twin-city structure*

The twin-city structure occurs in areas with two leading first-tier cities, such as Shenzhen and Guangzhou in the PRD urban agglomeration (Fig. 7) and Beijing and Tianjin in the BTH urban agglomeration (Fig. 8). The twin-city structure usually consists of two megacities close

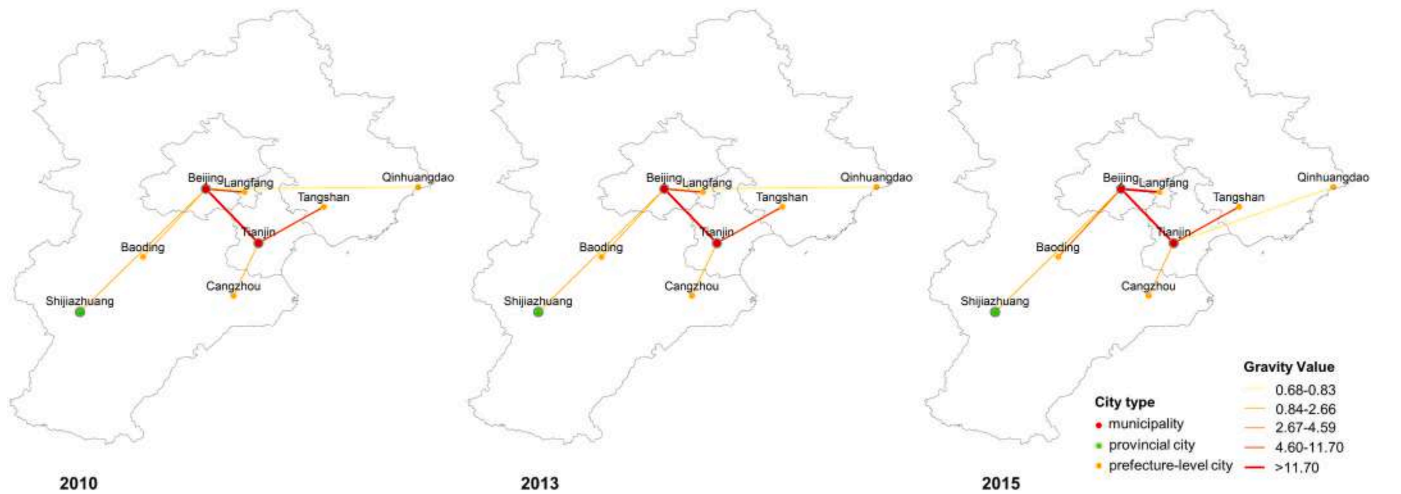

Fig. 8. Evolution of gravity values in the Beijing–Tianjin–Hebei urban agglomeration.

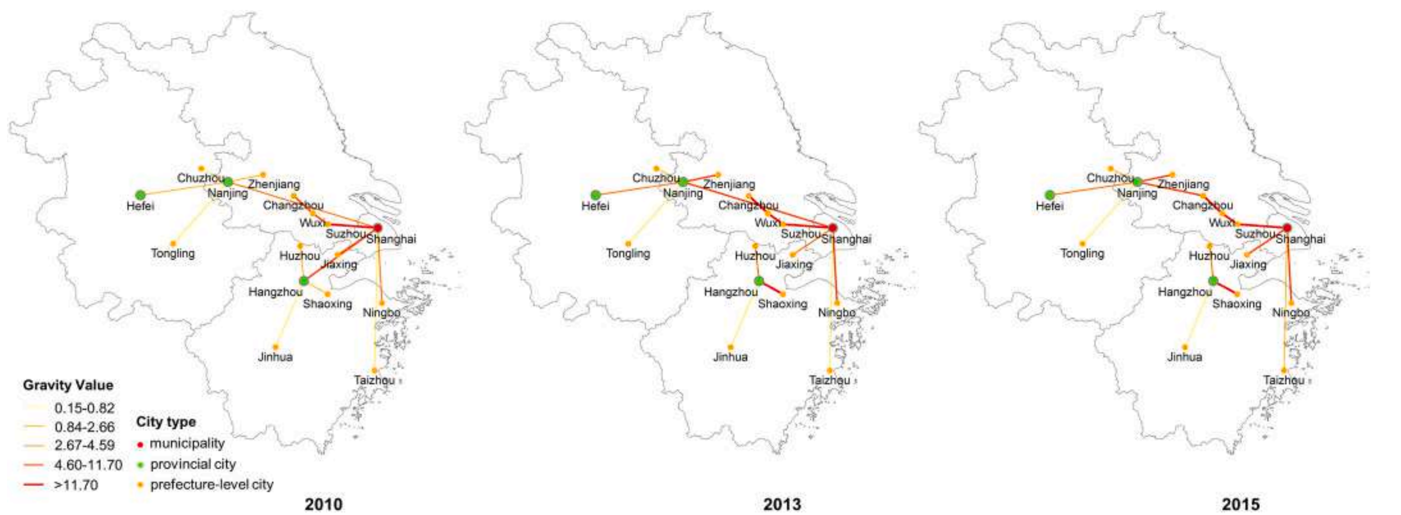

Fig. 9. Evolution of gravity values in the Yangtze River Delta urban agglomeration.

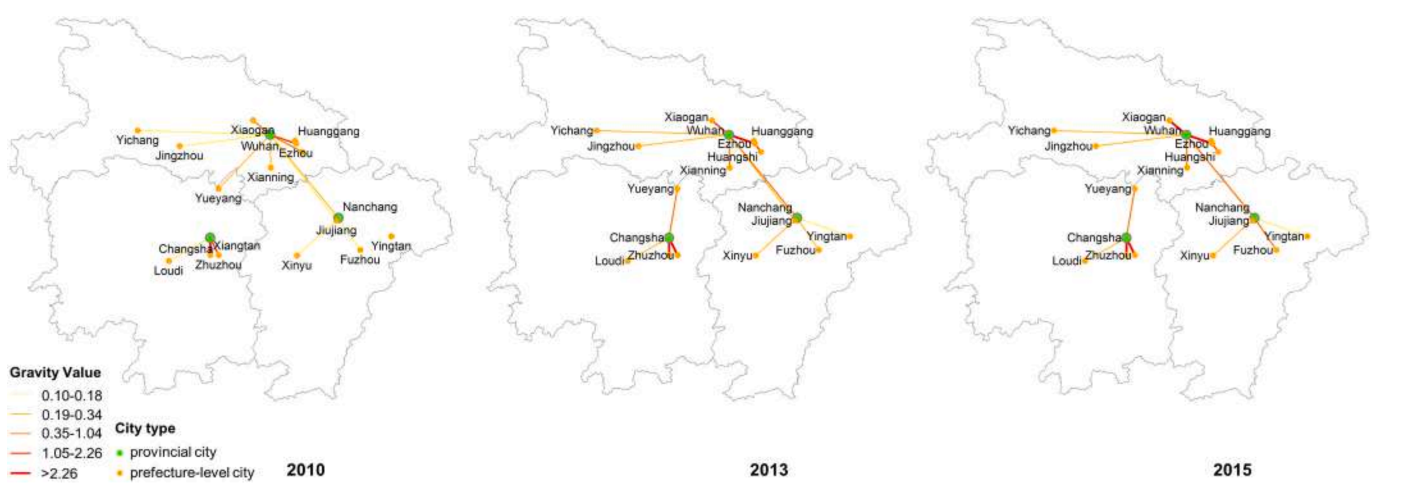

Fig. 10. Evolution of gravity values in the Yangtze River Middle Reaches urban agglomeration.

to each other, acting as an integrated regional center that not only influences surrounding areas, but also has a profound impact to the entire region. For example, the economic radiation area of Shenzhen covers southern and eastern Guangdong Province, whereas that of Guangzhou covers the rest of the province. Because Guangzhou and Shenzhen have a strong interrelationship, they jointly stimulate the economic development of the PRD region. Under the twin-city structure, second-tier cities tend to link with the nearest economic growth pole.

4.2.3. Polycentric structure

The polycentric structure tends to exist in urban agglomerations consisting of multiple core cities, such as the YRD region (Fig. 9) and the YRMR area (Fig. 10). Several leading first-tier cities easily form a stable polycentric structure, and the economic radiation capacity of each regional center continues to increase in the administrative area, resulting in an incessant enhancement of city status. Each first-tier city serves as the economic-growth pole influencing surrounding areas, consistent with the conclusion of (Wang & Zhao, 2018), whereas the cooperation between cities across boundaries promotes the integration of the entire urban agglomeration. For instance, a continuous metropolitan economic belt was constituted by five cities—Nanjing, Changzhou, Wuxi, Suzhou, and Shanghai—which also plays a significant role in promoting the balanced growth of the YRD region.

Urban spatial patterns are highly related to the significant role of cities in the region. Those cities with more developed economies would attract more investment and obtain more resources needed for the development, which results in a greater possibility to become the leading economic growth pole of the area. Thus, developed cities would strengthen their superior positionality over time. Besides, under a specific social context such as China, economic center cities are often political center cities, so provincial capital cities are most likely to form a monocentric structure, such as the Central Plains urban agglomeration. The formation of urban agglomerations has a strong administrative purpose and is highly policy-oriented. Therefore, the number of first-tier cities in the region determines the corresponding multi-center structure, such as the twin-city structure in the Pearl River Delta urban agglomeration.

4.3. Coupling HSR networks and economic networks

To better explore the relationship between an HSR network and urban economic growth, we chose HSR networks in the administrative area of the five representative urban agglomerations and the corresponding urban-gravity networks for comparative analysis. In 2010, only three cities in the PRD region could be reached by high-speed trains. Because the small number of cities could not accurately reflect the network connection between HSR and the regional economy, we excluded the calculation of QAP for 2010 in this region. As Table 3 shows, a strong positive correlation exists between HSR and economic development, and the coupling relationship between them is significant (all p values $< .05$). Table 3 indicates that HSR is highly related with regional economic development and distinct in separate areas.

The QAP analysis results vary in different urban agglomerations. The calculation results of the three world-class urban agglomerations in China—the YRD, PRD and BTH urban agglomerations—are all above 0.6; in contrast, the less developed central areas and the middle reaches of the Yangtze River remain relatively low, all below 0.4. It seems that a stronger linkage between HSR and regional economic development exists in areas where the economy is more developed and HSR tends to play a more prominent role in promoting regional integration in more developed areas, which is similar to the findings of (C.L. Chen & Vickerman, 2017) that HSR seems to have a better promotion in the integration of cities on HSR network in areas with more developed economies.

Table 3
Results of QAP calculations.

Urban agglomeration	2010	2011	2012	2013	2014	2015
YRD	0.642	0.632	0.638	0.647	0.646	0.649
PRD	–	0.741	0.773	0.764	0.802	0.804
BTH	0.874	0.893	0.746	0.796	0.812	0.801
CP	0.214	0.311	0.425	0.349	0.303	0.407
YRMR	0.203	0.239	0.158	0.153	0.210	0.216

Note. YRD = Yangtze River Delta urban agglomeration, PRD = Pearl River Delta urban agglomeration, BTH = Beijing–Tianjin–Hebei urban agglomeration, CP = Central Plains urban agglomeration, YRMR = Yangtze River Middle Reaches urban agglomeration, all p values $< .05$.

However, this does not mean that the strongest (weakest) positive relationship only occurs in the region where the highest (lowest) economic performance exists. The results of gravitational value revealed that the PRD region has the highest level of economic development (average gravity value between cities is 2.46) and the CP urban agglomeration is the least developed (average gravity value between cities is 0.08), but the QAP analysis showed that the linkages between HSR and the regional economy in the BTH region were strongest before 2011, and the connections in the middle reaches of the Yangtze River have always been the weakest. The reason might be that China's first HSR is the Beijing–Tianjin line, operating beginning in 2008. Since then, the construction of the HSR network has been expanding to other regions of the country with Beijing as the core city node. Thus, the shrinkage effect of time and space brought by HSR exerting on the BTH region is more obvious compared with other urban agglomerations. Also, more preferential policies are inclined to Beijing, due to the city's political status, so the economic benefits obtained through HSR links between regions are also greater. However, the middle reaches of the Yangtze River are a cluster of three metropolitan areas in essence: The Wuhan City Circle, the Changsha–Zhuzhou–Xiangtan metropolitan area, and the Poyang Lake metropolitan area. Therefore, the HSR transportation network is more mature within provincial boundaries, and production factors (mainly labor resources) tend to be concentrated in the economic center of the region—the provincial capitals—which leads to a relatively low level of factor concentration and resource flow across provinces. As a result, a positive promotional and complementary relationship between HSR transportation and regional development from the aspect of the whole area is not as obvious as the three world-class urban agglomerations in China. However, from the perspective of significance level, the HSR and the regional economy still have a positive association in the middle reaches of the Yangtze River.

From the results of QAP analysis, the urban agglomerations reveal two different trends, continuous growth and dynamic stability. Continuous growth indicates that the integration of HSR and regional economic growth achieves desirable results, and HSR articulates with urban development well. For example, interrelationships between HSR and economic growth have been strengthening in the CP region, increasing from 0.214 in 2010 to 0.407 in 2015, which means the area is experiencing the benefits from the new transportation technology. During the period, the operation of Zhengzhou (located in CP) with the Wuhan (in YRMR) line and Beijing (in BTH) on the Zhengzhou (in CP) line greatly shortened spatial distances and accelerated connections between the three urban agglomerations of BTH, YRMR, and CP, providing opportunities for economic growth in the CP area. Also, two newly built HSR lines in the CP agglomeration greatly enhanced economic relationships in the region.

The trend of being stable may indicate that there exists a positive correlation between transportation infrastructure and economic development in these areas, but the advantages of their interaction have not been further developed. In addition, we can find that the common characteristics of the two urban agglomerations whose QAP results keep growing are that the administrative areas of the two are all individual provinces. For example, the PRD urban agglomeration is within the scope of Guangdong Province, while almost all cities of the CP urban agglomeration are located in Henan Province. Therefore, the coupling relationship between HSR and regional economic development seems to be more significant within a smaller boundary scope, and less obvious in cross-administrative areas. In other words, the complementary effect between HSR and urban development within an individual area is better than that of cross-administrative regions.

5. Conclusions

As a new form of transportation, HSR has stimulated a great deal of research and attentions in developed regions, but is still emerging in developing economies. To further explore how the new transportation technology influences under different economic and social conditions, the largest emerging market in the world is selected. China provides an ideal case to study the significant role of the new transportation infrastructure in economic development under the context of rapid urbanization in emerging economies.

Previous studies on the impacts of HSR on economic development largely focused on analysis in a specific area (Li et al., 2016; Zhao et al., 2017). Considering that the influential mechanism between transportation and economic growth may be distinct in different regions, we selected five representative regions for discussion and analysis, aiming to eliminate the fortuity and uniqueness of the conclusion. In method application, this paper extends the research of Lao et al. (2016) and adds spatial and dynamic time attributes.

We examined the temporal and spatial evolution characteristics of China's HSR system and urban agglomerations during the period 2008–2015 and the dynamic relationship between them. The construction and expansion of high-speed rails spread from developed areas to underdeveloped areas, and as the amount of high-speed rail lines continues to increase, the entire HSR network is becoming more and more sparse, decreasing from 0.232 to 0.115; Areas with large commuting population and market potential are more likely to become transportation hubs, such as the YRD region, which is similar to the findings of (Jiao et al., 2017) that HSR cities with high values tend to concentrate in populous areas with well-developed economies; This type of transportation technology has reshaped urban hierarchy structure, and as a result, the status of emerging HSR hubs have gradually surpassed conventional railway-hub cities.

Within the boundaries of urban agglomerations, the economic radiation impacts of regional core cities are continually strengthening, gradually forming stable core–peripheral structures under various economic and geographical conditions, such as monocentric, twin-city, and polycentric structure. The formation of these multi-center structures is significantly linked to city characteristics and administrative scopes under specific national context. Further, from the aspect of economy development, the coefficients of more developed areas are all above 0.6, while that of less developed areas are all below 0.4, so a strong coupling relationship between HSR system and urban economic growth exists in those areas with more developed economies, which is similar to (C.L. Chen & Vickerman, 2017). As the HSR promotes regional economic development, the fast-growing economy has also stimulated the improvement of the national HSR system. From the aspect of geographical space, the complementary relationship between HSR system and urban economic growth is more obvious within a smaller administrative scope than cross-administrative areas. Thus, transportation technology is of necessity to develop, however, the boundary of urban agglomeration area should be determined with a comprehensive consideration of the complementarity roles between regions, instead of simply merging several individual areas together. This way, HSR and the urban agglomeration economy could achieve the best coupling effect.

In this study, we selected five representative urban agglomerations as the epitome of China and explored the coupling relationship between HSR and regional economic growth nationwide. However, the western part of China has not formed an influential urban agglomeration. This part of data needs to be supplemented in future research. In addition, we measured the economic linkages between cities in this paper using a simplified gravity model, which may differ from actual economic activity. A more accurate method to quantify and analyze the economic relationships between cities should be developed in the future. Besides, an objective assessment of the relationship between HSR and economic performance should consider the high investment, cost and environmental impacts of HSR projects. However, we did not consider as the scope of this research and thus did not address, it could be further investigated in the future study.

The main contribution of this research is to provide a "double-network" perspective in exploring the relationship between new forms of transportation and regional economic development by establishing HSR network and economic network respectively, and to analyze the performance differences of the dynamic coupling relationships in different areas, which can provide theoretical basis for city network theory and empirical evidences for further in-depth study of the relationship between transportation infrastructure and regional economic growth. The proposed research framework can be also applied to economic analysis in other countries with rapid economic growth. The speed and scale of urban transformation brought by emerging transportation infrastructure in developing countries is a major challenge, and many cities consider HSR an opportunity for the development of HSR stations and surrounding areas to enhance cities' competiveness, while the practical performance requires more empirical evidences (Liu & Ye, 2019). Balanced promotion of a regional economy requires further improvement in the transportation infrastructure represented by HSR, as well as in policy orientation and value chain governance (Lin, Zhang, & Wang, 2017). New types of transportation should not be viewed as isolated transportation systems, but rather to integrate with other modes of existing transportation (e.g., subway, railway, and highway), and together contribute to the overall development of economic growth at the national level.

CRediT authorship contribution statement

Ying Guo: Funding acquisition, Conceptualization, Investigation, Formal analysis, Writing - original draft. **Yilong Han**: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Biao Li**: Conceptualization, Investigation, Formal analysis, Writing - original draft.

Acknowledgements

This material is based in part upon work supported by the National Natural Science Foundation of China under Grant No. 71704134. This research is also supported by the Fundamental Research Funds for the Central Universities. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

References

Abhishek, N., Jenamani, M., & Mahanty, B. (2017). Urban growth in Indian cities: Are the driving forces really changing? *Habitat International, 69*, 48–57. https://doi.org/10.1016/j.habitatint.2017.08.002.

Ali, M. A. M. (2012). *Opportunities for high-speed railways in developing and emerging countries: A case study Egypt*.

Barthélemy, M. (2011). Spatial networks. *Physics Reports, 499*(1–3), 1–101. https://doi.org/10.1016/j.physrep.2010.11.002.

Butts, C. T. (2008). Social network analysis: A methodological introduction. *Asian Journal of Social Psychology*. https://doi.org/10.1111/j.1467-839X.2007.00241.x.

Camagni, R. P., & Salone, C. (1993). Network urban structures in northern Italy: Elements for a theoretical framework. *Urban Studies, 30*(6), 1053–1064. https://doi.org/10.1080/00420989320080941.

Campos, J., & de Rus, G. (2009). Some stylized facts about high-speed rail: A review of HSR experiences around the world. *Transport Policy, 16*(1), 19–28. https://doi.org/10.1016/j.tranpol.2009.02.008.

Cao, J., Liu, X. C., Wang, Y., & Li, Q. (2013). Accessibility impacts of China's high-speed rail network. *Journal of Transport Geography, 28*, 12–21. https://doi.org/10.1016/j.jtrangeo.2012.10.008.

Cao, W., Feng, X., & Zhang, H. (2019). The structural and spatial properties of the high-speed railway network in China: A complex network perspective. *Journal of Rail Transport Planning and Management*. https://doi.org/10.1016/j.jrtpm.2018.10.001.

Carrère, C. (2006). Revisiting the effects of regional trade agreements on trade flows with proper specification of the gravity model. *European Economic Review, 50*(2), 223–247. https://doi.org/10.1016/j.euroecorev.2004.06.001.

Chang, J., & Lee, J. H. (2008). Accessibility analysis of Korean high-speed rail: A case

study of the Seoul metropolitan area. *Transport Reviews, 28*(1), 87–103. https://doi.org/10.1080/01441640701421495.
Chen, C., & Vickerman, R. (2017b). Can transport infrastructure change regions' economic fortunes? Some evidence from Europe and China. *Regional Studies, 51*(1), 144–160. https://doi.org/10.1080/00343404.2016.1262017.
Chen, C. L. (2012). Reshaping Chinese space-economy through high-speed trains: Opportunities and challenges. *Journal of Transport Geography, 22*, 312–316. https://doi.org/10.1016/j.jtrangeo.2012.01.028.
Chen, C. L., & Vickerman, R. (2017a). Can transport infrastructure change regions' economic fortunes? Some evidence from Europe and China. *Regional Studies, 51*(1), 144–160. https://doi.org/10.1080/00343404.2016.1262017.
Cheng, Y. S., Loo, B. P. Y., & Vickerman, R. (2015). High-speed rail networks, economic integration and regional specialisation in China and Europe. *Travel Behaviour and Society, 2*(1), 1–14. https://doi.org/10.1016/j.tbs.2014.07.002.
Chester, M., & Horvath, A. (2010). Life-cycle assessment of high-speed rail: The case of California. *Environmental Research Letters, 5*(1), Article 014003. https://doi.org/10.1088/1748-9326/5/1/014003.
Deng, T., Wang, D., Yang, Y., & Yang, H. (2019). Shrinking cities in growing China: Did high speed rail further aggravate urban shrinkage? *Cities*. https://doi.org/10.1016/j.cities.2018.09.017.
Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal, 45*(2), 6–19. https://doi.org/10.1002/pmj.21409.
Guirao, B., Campa, J. L., & Casado-Sanz, N. (2018). Labour mobility between cities and metropolitan integration: The role of high speed rail commuting in Spain. *Cities, 78*, 140–154. https://doi.org/10.1016/j.cities.2018.02.008.
Hong, J., Chu, Z., & Wang, Q. (2011). Transport infrastructure and regional economic growth: Evidence from China. *Transportation, 38*(5), 737–752. https://doi.org/10.1007/s11116-011-9349-6.
Hou, Y. H., Liu, Z. B., & Yue, Z. G. (2009). Social network analysis over the process of economic integration in the Yangtze River Delta. *China Soft Science, 12*, 90–101.
Hou, Q., & Li, S. M. (2011). Transport infrastructure development and changing spatial accessibility in the Greater Pearl River Delta, China, 1990–2020. *Journal of Transport Geography, 19*(6), 1350–1360. https://doi.org/10.1016/j.jtrangeo.2011.07.003.
Jiao, J., Wang, J., & Jin, F. (2017). Impacts of high-speed rail lines on the city network in China. *Journal of Transport Geography, 60*, 257–266. https://doi.org/10.1016/j.jtrangeo.2017.03.010.
Jung, W.-S., Wang, F., & Stanley, H. E. (2008). Gravity model in the Korean highway. *EPL (Europhysics Letters), 81*(4), 48005. https://doi.org/10.1209/0295-5075/81/48005.
Krackardt, D. (1987). QAP partialling as a test of spuriousness. *Social Networks, 9*(2), 171–186. https://doi.org/10.1016/0378-8733(87)90012-8.
Krings, G., Calabrese, F., Ratti, C., & Blondel, V. D. (2009). Urban gravity: A model for inter-city telecommunication flows. *Journal of Statistical Mechanics: Theory and Experiment, 2009*(7), Article L07003. https://doi.org/10.1088/1742-5468/2009/07/L07003.
Lao, X., Zhang, X., Shen, T., & Skitmore, M. (2016). Comparing China's city transportation and economic networks. *Cities, 53*, 43–50. https://doi.org/10.1016/j.cities.2016.01.006.
Lee, T. (2019). Network comparison of socialization, learning and collaboration in the C40 cities climate group. *Journal of environmental policy & planning, 21*(1), 104–115.
Li, X., Huang, B., Li, R., & Zhang, Y. (2016). Exploring the impact of high speed railways on the spatial redistribution of economic activities - Yangtze River Delta urban agglomeration as a case study. *Journal of Transport Geography, 57*, 194–206. https://doi.org/10.1016/j.jtrangeo.2016.10.011.
Lin, S., & Song, S. (2002). Urban economic growth in China: Theory and evidence. *Urban Studies, 39*(12), 2251–2266. https://doi.org/10.1080/004209802200003385.
Lin, X., Zhang, Z., & Wang, M. (2017). Value and governance of high-speed railway. *Frontiers of Engineering Management, 4*(4), 463. https://doi.org/10.15302/j-fem-2017054.
Lindgren, K. O. (2010). Dyadic regression in the presence of heteroscedasticity—An assessment of alternative approaches. *Social networks, 32*(4), 279–289.
Liu, G., & Ye, K. (2019). Interactive effects of high-speed rail on nodal zones in a city: Exploratory study on China. *Frontiers of Engineering Management, 6*(3), 327–335. https://doi.org/10.1007/s42524-019-0051-2.
Ma, X., & Timberlake, M. F. (2008). Identifying China's leading world city: A network approach. *GeoJournal, 71*(1), 19–35. https://doi.org/10.1007/s10708-008-9146-8.
Mahutga, M. C., Ma, X., Smith, D. A., & Timberlake, M. (2010). Economic globalisation and the structure of the world city system: The case of airline passenger data. *Urban Studies, 47*(9), 1925–1947. https://doi.org/10.1177/0042098010372684.
Miao, H., & Zhou, H. (2017). A comparative analysis on economic linkage and hierarchical structure of the top three urban agglomerations in China — Using a synthesized gravity model. *Economic Geography, 37*(6), 52–59. https://doi.org/10.15957/j.cnki.jjdl.2017.06.008.
Morley, C., Rosselló, J., & Santana-Gallego, M. (2014). Gravity models for tourism demand: Theory and use. *Annals of Tourism Research, 48*, 1–10. https://doi.org/10.1016/j.annals.2014.05.008.
Opsahl, T., Agneessens, F., & Skvoretz, J. (2010). Node centrality in weighted networks: Generalizing degree and shortest paths. *Social Networks, 32*(3), 245–251. https://doi.org/10.1016/j.socnet.2010.03.006.
Perl, A. D., & Goetz, A. R. (2015). Corridors, hybrids and networks: Three global development strategies for high speed rail. *Journal of Transport Geography, 42*, 134–144. https://doi.org/10.1016/j.jtrangeo.2014.07.006.
Pöyhönen, P. (1963). A tentative model for the volume of trade between countries. *Weltwirtschaftliches Archiv, 90*(1963), 93–100. Retrieved from https://www.jstor.org/stable/40436776.
Rank, O. N. (2008). Formal structures and informal networks: Structural analysis in organizations. *Scandinavian Journal of Management, 24*(2), 145–161. https://doi.org/10.1016/j.scaman.2008.02.005.
Schweitzer, F., Fagiolo, G., Sornette, D., Vega-Redondo, F., Vespignani, A., & White, D. R. (2009). Economic networks: The new challenges. *Science, 325*(5939), 422–425. https://doi.org/10.1126/science.1173644.
Shaw, S. L., Fang, Z., Lu, S., & Tao, R. (2014). Impacts of high speed rail on railroad network accessibility in China. *Journal of Transport Geography, 40*, 112–122. https://doi.org/10.1016/j.jtrangeo.2014.03.010.
Sigler, T. J., & Martinus, K. (2017). Extending beyond "world cities" in World City Network (WCN) research: Urban positionality and economic linkages through the Australia-based corporate network. *Environment and Planning A: Economy and Space, 49*(12), 2916–2937. https://doi.org/10.1177/0308518X16659478.
Sun, Q., Tang, F., & Tang, Y. (2015). An economic tie network-structure analysis of urban agglomeration in the middle reaches of Changjiang River based on SNA. *Journal of Geographical Sciences, 25*(6), 739–755. https://doi.org/10.1007/s11442-015-1199-2.
Taaffe, E. J. (1962). The urban hierarchy: An air passenger definition. *Economic Geography, 38*(1), 1–14.
Taylor, P. J., Walker, D. R., Catalano, G., & Hoyler, M. (2002). Diversity and power in the world city network. *Cities, 19*(4), 231–241. https://doi.org/10.1016/S0264-2751(02)00020-3.
van Oort, F., Burger, M., & Raspe, O. (2010). On the economic foundation of the urban network paradigm: Spatial integration, functional integration and economic complementarities within the Dutch Randstad. *Urban Studies, 47*(4), 725–748. https://doi.org/10.1177/0042098009352362.
Verma, A., Sudhira, H. S., Rathi, S., King, R., & Dash, N. (2013). Sustainable urbanization using high speed rail (HSR) in Karnataka, India. *Research in Transportation Economics, 38*(1), 67–77. https://doi.org/10.1016/j.retrec.2012.05.013.
Wang, J., Jin, F., Mo, H., & Wang, F. (2009). Spatiotemporal evolution of China's railway network in the 20th century: An accessibility approach. *Transportation Research Part A: Policy and Practice, 43*(8), 765–778. https://doi.org/10.1016/j.tra.2009.07.003.
Wang, J., Mo, H., Wang, F., & Jin, F. (2011). Exploring the network structure and nodal centrality of China's air transport network: A complex network approach. *Journal of Transport Geography, 19*(4), 712–721. https://doi.org/10.1016/j.jtrangeo.2010.08.012.
Wang, K., Deng, Y., Sun, D., & Song, T. (2014). Evolution and spatial patterns of spheres of urban influence in China. *Chinese Geographical Science, 24*(1), 126–136. https://doi.org/10.1007/s11769-013-0635-4.
Wang, L., & Duan, X. (2018). High-speed rail network development and winner and loser cities in megaregions: The case study of Yangtze River Delta, China. *Cities, 83*, 71–82. https://doi.org/10.1016/j.cities.2018.06.010.
Wang, L., & Zhao, P. (2018). From dispersed to clustered: New trend of spatial restructuring in China's metropolitan region of Yangtze River Delta. *Habitat International, 80*(July), 70–80. https://doi.org/10.1016/j.habitatint.2018.08.005.
Wanke, P., Chen, Z., Liu, W., Antunes, J. J. M., & Azad, M. A. K. (2018). Investigating the drivers of railway performance: Evidence from selected Asian countries. *Habitat International, 80*(April), 49–69. https://doi.org/10.1016/j.habitatint.2018.08.004.
(Ato)Xu, W., & Huang, Y. (2019). The correlation between HSR construction and economic development – Empirical study of Chinese cities. *Transportation Research Part A: Policy and Practice.*. https://doi.org/10.1016/j.tra.2019.05.017.
Zhao, J., Yu, Y., Wang, X., & Kan, X. (2017). Economic impacts of accessibility gains: Case study of the Yangtze River Delta. *Habitat International, 66*, 65–75. https://doi.org/10.1016/j.habitatint.2017.05.005.