Graph theoretical analysis of the Chinese high-speed rail network over time

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Abstract:

In this paper, we examine the development of the Chinese HSR network over the period 2003-2014. Our methodology relies on network analysis to identify changes over time in HSR network accessibility measured by node degree, strength, closeness, and betweenness. We show that sub-networks connecting regional centres with second-tier cities are first built. Once such sub-networks are mostly established, they are also connected with each other. Moreover, a simultaneous rather than a sequential schedule for multiple HSR segments is at place at any particular time. Finally, we show that the HSR network expands all the lower-elevation, more populous and prosperous regions. Although some clusters are critical politically, HSR network development is still mainly driven by economic factors, which is reflected from the fact that nodes in the more economically vibrant regions present a higher number of routes passing through and higher service quality (i.e., lower travel time). Finally, in order to illustrate the uniqueness of the Chinese HSR development pattern, we briefly discuss and compare the HSR development in other Asian markets, notably Taiwan, South Korea and Japan.

1. Introduction

High-speed rail (HSR) has been a focal element of transport policies in many countries while pursuing various goals: alleviating congestion on conventional rail, road or air networks, accelerating economic development and integration, as well as reducing the environmental impact of the transport industry. According to the International union of railways (UIC, 2017a), in 2015 HSR systems have carried over 240 billion passenger-km, a 20% increase compared with 2010. The leading investors in HSR are China and Japan. Japan, who pioneered investment in HSR, operates 3,041 km of HSR, it is constructing 402 km and plans to build additional 194 km by 2046 (UIC, 2017b). The Chinese HSR network has been driving the growth of HSR traffic in the period 2013-2015 (see Figure 1) and remains the largest in the world. The opening, in 2017, of two new HSR lines – Baoji-Lanzhou and Shijiazhuang-Jinan – marked significant progress in the construction of China's HSR network, which now includes four north-south routes and four east-west ones (Chinadaily.com, 2018). As of 2017, the network covers 23,914 km and is planned to cover an addition of 12,255 km, with 10,730 km of lines already under construction (UIC, 2017b).

==Insert Figure 1 about here==

Such aggressive expansion is unprecedented in other markets as HSR networks in many countries are much smaller (see also section 6). The Chinese HSR network development may exhibit some unique patterns, raising interest for substitutes transport modes to come up with effective planning and response strategies (Fu et al., 2012). For instance, while the Chinese airline industry is likely to continue its fast-paced growth in the coming years, the patterns of airport system development and airline network choice will likely experience some major changes due to inter-modal competition (Fu et al., 2012). This study aims to provide a comprehensive analysis of the development of the Chinese HSR network over the period 2003-2014 so that the pattern of HSR expansion can be clearly identified, thus stakeholders including operators of substitute transport modes can be better prepared for the challenges. In addition, as countries including Brazil, India, Russia, and the US are evaluating the option of investing in HSR, we hope that our study shed some light to these on-going planning processes.[1]

Our methodology relies on network analysis in order to identify changes over time in HSR network accessibility.[2] In graph theory and network analysis, indicators of centrality classify the most important vertices within a graph. Applications include identifying the most influential person(s) in a social network, key infrastructure nodes in the Internet or transport networks (Newman, 2010). In our context, the HSR network is represented as a weighted oriented graph and weights on HSR routes represent the performance of HSR service supply and population/per capita income of origin and destination cities connected by the HSR routes. Following Freeman (1978) and Opsahl et al. (2010), we consider four different measures of node centrality (degree, strength, closeness, and betweenness) and identify the evolution of such measures over the period 2003-2014. With respect to the methodology, this paper is similar to Erath et al. (2009), which investigates the development of the Swiss road and railway network, Wang et al. (2011) and Lin (2012) for the case of the Chinese air transport network, or To (2015) for the case

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[1] In the United States, there is a vigorous public debate about HSR. In 2009, the American Recovery and Reinvestment Act set aside $8 billion for HSR investments: the Federal Railroad Administration initially disbursed the money to six major corridors, but Florida, Ohio and Wisconsin returned the funding. As of July 2017, HSR is in operation along the Northeast corridor, connecting Boston, New York and Washington DC, and it is planned to link Sacramento, San Francisco and Los Angeles (UIC, 2017b).

[2] Other than network analysis, qualitative methodologies are also frequently adopted to describe the evolution of transport systems (see Ng et al, 2018b).

of Hong Kong urban rail system. Degree and strength can be both indicators of the level of the local involvement of a station in the surrounding network. Conversely, closeness and betweenness centralities are considered to capture global features such as whether a station can assert control over the traffic flow in the network. By analysing the evolution over time of node centralities, our approach is able to identify the pattern of HSR sub-networks development and how connections among multiple sub-networks have been deployed over time.

The paper is organised as follows. Section 2 presents a review of relevant literature. Section 3 discusses the methodology, while Section 4 presents the case study. In Section 5, we present our findings and related discussion. Section 6 presents comparatively HSR deployment in other regions of the Asian markets, while Section 7 contains concluding remarks.

2. Relevant literature

This paper relates to different strands of research. A first related bunch of papers focuses on different classifications of HSR models. This literature abstracts away from the analysis of HSR accessibility over time, which is the focus of our paper. Campos and De Rus (2009) identify four models: (i) exclusive exploitation (either HSR trains on HSR tracks or conventional trains on conventional tracks); (ii) mixed HSR (HSR trains on HSR and conventional tracks); (iii) mixed conventional (conventional trains on HSR or conventional tracks), and (iv) fully mixed (HSR and conventional trains on HSR or conventional tracks).[3] The exclusive exploitation model has been adopted by the Japanese Tokaido Line, where HSR service first introduced in 1964 uses standard gauge, while Japanese conventional lines uses narrow gauge. Chinese HSR started as mixed HSR model by upgrading conventional lines, but then majority of the lines are newly added and are dedicated to HSR services (i.e., exclusive exploitation model). This has involved a large amount of investment on infrastructure but has allowed more intensive usage of infrastructure and thus higher traffic capacity (Fu et al., 2012). More recently, Perl and

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[3] The exclusive exploitation and the mixed high speed models allow a more intensive usage of HSR infrastructure, whereas the other models must take into account that (with the exception of multiple-track sections of the line) slower trains occupy a larger number of slots during more time and reduce the possibilities for providing HSR services.

Goetz (2015) identify three strategic models: (i) exclusive corridors, between megacities of more than 10 million inhabitants, (ii) hybrid networks, made of new HSR links connecting conventional rail lines, which remain crucial, multiplying the number of origins and destinations to be served; and, (iii) comprehensive national networks, with new infrastructure linking all major and mid-sized communities across the country. The Japanese Tokaido Line is a key example of dedicated HSR corridor. It originally linked Tokyo and Osaka with dedicated HSR tracks (512 km), but it has been later expanded to serve smaller cities. On the other hand, China provides a pivotal example of comprehensive grid network with a backbone made up by north–south and east–west passenger dedicated lines. The authors conclude that certain attributes of each of these models have experienced more success than others, with HSR being generally profitable in heavily travelled corridors of 300–800 km between major population centers (i.e., Tokyo-Osaka line), while longer distance HSR operations involving smaller population centers can struggle to cover their costs. In China, performance seems closely related to the population and economic strength of cities they serve (China.com, 2016). The expanded HSR train network in China has started to make a profit in the populated east. In 2015, six HSR lines made a profit, with the Beijing-Shanghai route topping the list at a net profit of US$990 million, all connecting mega cities in populated areas with strong economies such as Beijing, Tianjin, Shanghai, Hangzhou, Ningbo, Shenzhen and Guangzhou. Except for the Beijing-Tianjin HSR, the other five lines have managed to turn from deficit to profit within five years of operations. Conversely, services running through the vast central and western regions are still far from breaking even. For instance, the Zhengzhou-Xi'an HSR has run at a loss since it began operating in 2010, when passenger volume failed to reach half of capacity.

A second bunch of related papers abstracts away from network categorization and focuses on the impact of rail network extensions on accessibility and spatial equity in China. Wang et al. (2009) find that the spatial structure of China’s railway network is characterized by “concentric rings” with its major axis in North China and the most accessible city gradually migrating from Tianjin to Zhengzhou. The authors focus on a time span of about one century (1906–2000) and abstract away from accessibility changes due to the introduction of HSR services, which is the focus in our paper. Cao et al. (2013) measure accessibility of 49 Chinese cities (mostly, provincial capitals and municipalities) in 2011 and find that the central-eastern cities have gained more benefits from HSR introduction in terms of average travel time and number of daily accessible cities. Measures of potential accessibility, reflecting the opportunities/activities at location, e.g., the distribution of production, provide high values for cities along the Beijing–Shanghai axis and in the Pearl River Delta Region. Jiao et al. (2014) measure accessibility of 333 prefecture-level cities in 2012. Results show that accessibility increased with HSR introduction but inequalities increased as well among cities with different population size and cities that differ in the shortest distance to HSR stations.[4] We complement Cao et al. (2013) and Jiao et al. (2014) as we analyse the changes in HSR network configuration and accessibility over time to identify the pattern of the development. Shaw et al. (2014) analyse the changes in travel time, travel cost, and distance accessibility for each of the four main stages of HSR development in China: no HSR service before August 2008, several HSR lines between August 2008 and July 2011, reduced operating speed of HSR trains between August 2011 and November 2012, and addition of new HSR lines and reduction of ticket fares between December 2012 and January 2013. Results show that cities along HSR lines see much larger increase in accessibility ("corridor effect"). Both travel cost and travel distance accessibility display a "radial" pattern with Beijing–Tianjin–Hebei and the accessibility decreases while moving toward periphery areas. As opposite to Shaw et al. (2014), we treat 2003 as the beginning of our analysis (same as Ollivier et al., 2014). Indeed, starting from 2008, investments in HSR grew substantially, as partially driven by the financial crisis unveiled in 2007-2008 and different sub-networks connecting regional centres with second-tier cities have been built in China (see Section 4.1).

Finally, a vast branch of literature on HSR development focuses on the intermodality between HSR and air transport, which are relatively close substitutes in selected

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[4] Some contributions confirm that major accessibility improvements are usually confined to existing large cities having HSR stations within this corridor because of their initial locational advantage (Gutiérrez, 2001; Martin et al., 2004). On the contrary, cities not served by HSR may suffer from relative disadvantages because of the relative loss of travel time to other cities (Garmendia et al., 2012; Kim and Sultana, 2015). Thus, the isolation from the initial HSR network may intensify spatial disparities of interactions among cities.

markets.[5] Some contributions focus on the market equilibrium of airline-HSR competition (i.e., traffic and price levels, as well as long-term impacts) (e.g., Yang and Zhang, 2012; D'Alfonso et al., 2015, 2016; Jiang and Zhang, 2016; Wan et al., 2016) and airline-HSR cooperation (Avenali et al., 2018; Jiang and Zhang, 2014; Jiang et al., 2017; Xia and Zhang, 2016; 2017; Li et al., 2018; Xia et al, 2018). Recently, HSR network expansion has been analyzed from the perspective of HSR-low cost carriers interaction depending on whether HSR expansion is planned in highly populated and developed corridors or low-density corridors (Jiang and Li, 2016; Wang et al., 2017). Generally, results show that the introduction of HSR services severely affected the competitiveness of air transport in China (Fu et al., 2012; Zhang et al., 2014; Wang et al., 2018), and the air demand has become much more elastic after the introduction of parallel HSR service (Zhang et al., 2017). Recent cases of air route cancellations include a number of Chinese domestic markets, such as Zhengzhou-Xi'an, Nanjing-Shanghai, Changsha-Guangzhou and Wuhan-Nanjing, whereas daily flights on the Wuhan-Guangzhou route (1,069 km) were reduced from fifteen to nine, one year after the HSR entry (Fu et al., 2012).[6] In our paper, we abstract away from the discussion on the effects of HSR introduction over the competitiveness of air transport, in order to focus on the analysis of changes in HSR network accessibility on the time span 2003-2014. Our analysis could inform about the pattern of HSR expansion, thus stakeholders including substitute air transport operators can be better prepared for the challenges due to intermodality.

3. Methodology

The HSR network is described as a weighted oriented graph, $G \coloneqq (N, E)$ where N is the set of nodes and E is the set of ordered edges. Each node i, with $i \in N \coloneqq \{1, \dots, n\}$, represents an HSR station, where n is the total number of HSR stations in the network. Each oriented edge $ij \in E \coloneqq \{ij | i \in N, j \in N, i \neq j\}$ represents a train route from node i

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[5] Rothengatter (2011) finds evidence that fierce competition between air transport and HSR may occur on routes with distance up to 1000 km, mostly likely between 400 and 800 km. Steer Davies Gleave (SDG, 2004) concludes that the threat imposed by HSR on air travel is the strongest in countries with a large market for travel over distances of around 200-800 km, and particularly in the range 300-600 km.

[6] Deep cuts of airfares after the entry of HSR service are also very common. For example, the market between Wuhan and Xiamen, two Chinese cities recently linked by HSR, saw an 80% drop in air ticket price (Jiang and Zhang, 2014).

to node j. Finally, let w_{ij} be the weight associated to the edge $ij \in E$. The value w_{ij} is defined as greater than 0 if HSR station i is connected to station j, and the value represents the weight of the route connecting i to j. For non-social networks, weights are proxy of the operational performance of edges.

3.1 Local analysis

Degree and strength can be both indicators of the level of involvement of a station in the surrounding network. Thus, it is important to incorporate both these measures when studying the local centrality of a station.

- *Degree centrality*

Degree centrality is the number of adjacencies in a network, i.e., the number of nodes that the focal node is connected to, and thus measures the involvement of the node in the network. Following the notation in Opsahl et al. (2010), we define HSR station degree as:

$$C_D(i) = \sum_{j=1, j\neq i}^{n} x_{ij} \tag{1}$$

where $i \in N$ is the focal HSR station, $j \in N$ represents all other HSR stations. The value x_{ij} is defined as 1 if station i is connected to station j, and 0 otherwise. In other words, x_{ij} is defined as 1 if the route $ij \in E$ exists.

The degree centrality of an HSR station is a good proxy of the local structure around the station.

- *Strength*

Degree has generally been extended to the sum of weights when analysing weighted networks (Barrat et al., 2004), i.e., *node strength*. Following the notation in Opsahl et al. (2010), we define HSR station strength as follows:

$$C_D^w(i) = \sum_{j=1, j \neq i}^{n} w_{ij} \tag{2}$$

Since strength takes into consideration the weights of edges between two nodes, this has been the preferred measure for analysing weighted networks (Opsahl et al., 2010).

3.2 Global analysis

The degree measure does not take into consideration the global structure of the HSR network. For example, although an HSR station might be connected to many others, the connection might not be quick (Opsahl et al., 2010). Moreover, we note that node strength only takes into consideration a node's total level of involvement in the surrounding network. Therefore, in our setting, station strength does not take into consideration the number of other stations that are indirectly connected. To capture global features, closeness and betweenness centrality are considered.

The closeness and betweenness centrality measures rely on the identification and length of the shortest paths among HSR stations in the network. In an unweighted network, shortest path between two nodes is found by minimizing the number of intermediary nodes, and its length is defined as the minimum number of edges linking the two nodes, either directly or indirectly. In our context, the minimum number of intermediary HSR stations between the two focal stations in a given route should be taken into account. Following notation in Opsahl et al. (2010), it can be formalized as:

$$d(i,j) = min_h\left(x_{ih} + \cdots + x_{hj}\right) \tag{3}$$

where h are intermediary stations on route between station i and station j and the value x_{ih} is defined as 1 if station i is connected to station h, and 0 otherwise.

However, in weighted networks, the shortest path is generalized as:

$$d^w(i,j) = min_h\left(\frac{1}{w_{ih}} + \cdots + \frac{1}{w_{hj}}\right) \tag{4}$$

where w_{ih} is greater than 0 if HSR station i is connected to station h, and the value represents the weight of the route connecting i to h.

- *Closeness*

Closeness centrality is defined as the inverse of the length of the shortest paths from a node to all other nodes in the network. Thus the more central a node is, the closer it is to all other nodes. It measures how adjacent a focal HSR station is to all other stations in the network. Following notation in Opsahl et al. (2010), it can be formalized as:

$$C_C^{w*}(i) = \frac{1}{\left[\sum_{j=1,j\neq i}^{n} d^w(i,j)\right]} \tag{5}$$

If node i and j are not connected directly or indirectly, then $d^w(i,j)$ equals infinity and its reciprocal equals zero. Yet we could still calculate closeness for every HSR station despite whether it is isolated or not.

- *Betweenness*

Betweenness relies on the identification of the number of shortest paths that pass through a node. Higher betweenness value indicates that the HSR station is more frequently passed through by shortest paths between other stations. In so doing, a station can assert control over the flow. Following notation in Opsahl et al. (2010), it can be formalized as:

$$C_B^w(i) = \frac{g_{jk}^w(i)}{g_{jk}^w} \tag{6}$$

where g_{jk}^w is number of shortest paths between station j and station k and $g_{jk}^w(i)$ is the number of those paths that go through station i.

4. The Case of China

4.1 The Chinese HSR Network

Exactly when China started to enter the HSR era is controversial sometimes, depending on the different definitions of HSR adopted. In January 2004, the State Council (the chief administrative authority of China) executive meeting passed the Mid-to-long-term Railway Network Plan, in which an HSR network consisting of four vertical (north-south) and four horizontal (west-east) trunk routes with a combined track length over 12,000 km was first proposed. This is generally believed to be the beginning of the HSR network development. However, in October 2003, the Qin-Shen Passenger Designated Line (PDL), connecting Qinhuangdao and Shenyang in northern China, has been opened for use. It is an electrified dual-track railway designed for a top speed of 200 km/h (increased to 250 km/h in 2007 and 300 km/h in 2013). The opening of this line is widely accepted as a milestone in the development of the Chinese HSR system, marking the dawn of a rapidly developing era. Since the purpose of this paper is to analyse the dynamic pattern of the HSR development, we treat 2003 as the beginning of our analysis (same as Ollivier et al., 2014). Under the same rationale, we also incorporate all the upgraded existing lines that meet the speed standard of HSR into our analysis. Figure 2 shows the progression of the Chinese HSR network development.

== Insert Figure 2 about here ==

From 2003 to 2007 the growth of HSR track length was relatively slow, indicating a period of experimenting and experience gaining. Starting from 2008, the growth gained a substantially higher momentum. The speed of growth entered a new phase of booming after 2011, causing the total length of HSR tracks to more than double within 3 years. This was partially driven by the financial crisis unveiled in 2007-2008. With a weakened global demand, China transformed itself from an export-driven economy to rely on investment for GDP growth. The government rolled out a massive economic stimulus program totalling US$ 586 billion, which had been mainly used for infrastructure development. The Chinese HSR system is no doubt among one of the biggest beneficiaries of this surge of government-backed cheap credit.[7] However, since the long-term development of the system was planned before the crisis, we can assert that the stimulus package has fastened instead of changed the whole process.

4.2 Dataset

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[7] All transport system developments are highly related to government initiatives, see the relevant discussion in Ng et al. (2018a).

The dataset is constructed based on the public information published by the China Railway Corporation (for the HSR network related information) and the National Bureau of Statistics of China (for other supplemental information such as distance, population and per capita income). Our dataset covers the period 2003-2014. Consistently with the methodology in section 3, in each year we have mapped the Chinese HSR network as a weighted oriented graph and, accordingly, for each year we have calculated each station's degree, strength, closeness and betweenness. In our setting, weights on HSR routes represent the operational performance of the supply side and population/per capita income. Thus, the following weight measures have been considered for each year:

(1) *number of different HSR routes passing two stations*

(2) *train service class*: weight is 2 for HSR trains (G trains) and 1 for intercity trains (C trains) / CRH trains (D trains), based on the fact that G trains, with maximum speed in the range 300-350 km/h, are faster than C trains, with maximum speed equal to 300 km/h, and D trains, with maximum speed in the range 200-250 km/h.[8] In case different service classes are available between a pair of stations, the highest weight is used.

(3) *distance*: inverse distance is used as weight, so that shorter distance is equivalent to larger weight. In case different routes pass through a pair of stations, the highest weight is used.

(4) *train speed*: in case different routes pass through a pair of stations, the higher speed is used as weight.

(5) *travel time*: inverse travel time is used as weight, so that shorter travel time is equivalent to larger weight. Travel time is obtained by considering the ratio between the length of a specific route and the speed of the train used to cover that

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[8] In China there are seven types of passenger train services. Other than G, C and D trains there are Z, T, K and P trains which are, respectively, direct express trains (maximum speed equal to 160 km/h), express trains (maximum speed equal to 140 km/h), fast trains (maximum speed equal to 120 km/h) and general trains (maximum speed equal to 100 km/h)

route. In case different routes pass through a pair of stations, the highest weight is used.

(6) *population and per capita income:* those parameters are obtained as the average value observed between the origin and destination cities connected by the HSR routes.

5. Analytical Results

5.1 Local analysis

We first focus on local measures. Figure 3 shows the distribution of node degrees across years.

== Insert Figure 3 about here ==

The HSR network (or, more generally, the rail network) differs from the other types of transport networks such as the aviation network, mainly in that the node degrees cannot grow too large. This is because unlike aviation system, which has no specific infrastructure requirement in between the origin and the destination, the linking of two or more train stations require substantial (and irreclaimable) investment due to tracks building.[9]

From Figure 3, we can identify a local pattern of the Chinese HSR network development. In the period 2003-2010 there is a rapid increase of nodes with lower degrees. Then, nodes with higher degrees emerge. This is a first evidence of the following phenomenon: sub-networks that connect regional centres, i.e., megacities, with second-tier cities are first built. Once such sub-networks are mostly established, they are also connected with each other. For instance, this is the case for the development of the Beijing-Guangzhou-

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[9] Wang et al. (2011) study the air transport network of China in which the highest node degree is close to 100. In contrast, the Chinese HSR network has a maximum node degree of 6.

Shenzhen HSR route, which connects three of the four largest cities in the Mainland China and will extend to Hong Kong in 2017.[10]

Figure 4 is a collection of maps showing the node degrees for all HSR stations in different years.

== Insert Figure 4 about here ==

A close observation reveals that a simultaneous rather than a sequential schedule for multiple HSR segment is at place at any particular time. In Japan, for example, the opening of new HSR lines is always in sequence and normally connects with existing lines immediately (see also Section 6).[11] One consequence of the sequential schedule for multiple HSR segments is the amortization of the capital cost of construction equipment over a number of projects. Indeed, this is one of the major driving forces for China's significantly lower HSR building cost compared with the other countries (Ollivier et al., 2014): relatively low labour cost, large scale of the HSR network in place at a given phase, which has allowed the standardization of the construction elements, the development of technology capacity for equipment manufacturing and construction.

From Figure 4, we can easily see that the development of the Chinese HSR system has been clustered on the south and the east parts of the country. In particular, the network started to develop from the northern part (i.e., around Beijing). However, starting from 2013, the network started to develop in Central and East China thanks to their more central locations (i.e., Yangtze River Delta regions around Shanghai). From Figure 5 reporting China's topology (Panel A), population density (Panel B) and per-capita GDP (Panel C), we note that the HSR network expands all the lower-elevation, more populous and prosperous regions. Indeed, HSR has been found generally profitable in heavily travelled corridors between major population centres, while operations involving small population centres can struggle to cover their costs (Perl and Goetz, 2005).

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[10] The construction started in 2005. The Wuhan-Guangzhou section opened in December 2009, the Guangzhou-Shenzhen section opened in December 2011, the Zhengzhou-Wuhan section opened in September 2012, and the Beijing-Zhengzhou section was opened in December 2012.

[11] See https://www.nippon.com/en/features/h00078/ for the timeline of Japanese Shinkansen development.

== Insert Figure 5 about here==

In Figure 6, we present the strength of different nodes of the Chinese HSR network from 2011 to 2014 calculated with the first type of weight (number of different HSR routes passing two nodes). We thus evaluate the level of involvement of an HSR station in the network according to the number of routes passing through it.[12] Comparing Figure 6 with the corresponding panels in Figure 4, we can see that the involvement of the node in the northern cluster reduces while the one in the eastern cluster increases. These differences probably confirm that although the northern cluster around is critical politically, hence making the linkages relevant, HSR network development service is still mainly driven by economic factors, which is reflected from the fact that nodes in the more economically vibrant regions present a higher number of routes passing through.

== Insert Figure 6 about here ==

5.2 Global analysis

Degree and strength local centrality measures are indicators of the level of involvement of a station in the surrounding network cluster. Next, we shift the focus to the measures of closeness and betweenness centrality to assess the global involvement of a station in the network.

Since it is burdensome to make comparisons on city level, we divide China into seven geographical regions based on the classification proposed by Bai et al. (2015)[13] (Figure 7) and then rank these regions across years by average closeness and betweenness (Tables 1 and 2). Since both closeness and betweenness are about accessibility, here we present results calculated with respect to the last type of weights (travel time).[14] It should be noted that Northwest China is not in the rank due to the fact that the corresponding sub-network was not linked to the other sub-networks until 2014.

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[12] Results are confirmed with other weights although in different magnitude. Before 2011, the network was not established enough for the difference between node degree and strength to be sufficiently clear.

[13] The classification is based on GLCD-2005 (Geodata Land Cover Dataset for year 2005) land cover map of China at a scale of 1 to 250,000 produced by the Data Sharing Infrastructure of Earth System Science.

[14] Results are confirmed with other weights although in different magnitude.

== Insert Figure 7 about here ==

== Insert Table 1 about here ==

== Insert Table 2 about here ==

First, we may confirm that the HSR network started to develop from the northern cluster of the country, which might be due to three possible reasons. First, Beijing, the capital and political centre of China, is located in Northern China. Similar to Paris for France and Madrid for Spain, it makes political sense to first develop the subsystem around the capital city (see also Perl and Goetz, 2015). Second, it could be less technically challenging to develop HSR network in Northern China, due to the large areas of flat plains (see Figure 6A). Third, Northern China is one of the most populated areas in the country (see Figure 6B). However, starting from 2013, the Central and Eastern cluster show higher closeness and betweenness and confirm higher control over the network in terms of access time. Accordingly, the Southern cluster shows less control, mainly due to its peripheral location and weaker economic indicators.

The differences between the two ranks are also interesting, which are mainly due to the intrinsic distinction between the closeness and betweenness measures. The more central a node is, the closer it is to all other nodes (i.e., lower travel times to all other nodes). Higher betweenness value indicates that the HSR station is more frequently passed through by shortest paths (i.e., characterized by lower travel time) between other stations. When focusing on recent years, i.e., after 2013, we note that the Central cluster, due to its location, is heavily relied upon linking other clusters of the HSR network. Thus it is natural to have high betweenness. However, since the whole HSR network is significantly weighted to the east, it is also not surprising to see that Eastern cluster ranks higher in closeness.

6. Comparative Cases

Other countries with HSR, due to their much smaller scales and coverages, usually show development patterns that are very different from the Chinese one. In order to illustrate the uniqueness of the Chinese HSR development pattern, in this section, we briefly discuss the HSR development in other Asian markets, notably Taiwan, South Korea and Japan (see Figure 8).

== Insert Figure 8 about here==

Taiwan HSR runs along the west coast of Taiwan and network coverage reaches almost 90% of Taiwan's population (Cheng, 2010). It is the most representative case of the "exclusive corridor" development pattern: twelve stations are planned in the western corridor, with eight stations already open in Taipei, the political and economic center, Banciao, Taoyuan, Hsinchu, Taichung, Chiayi, Tainan, and Zuoying (Kaohsiung). A one-stop train takes just 90 min to travel from Taipei to Kaohsiung, a distance of 345 km, while a train that stops at all stations takes 120 min to reach Zuoying. THSRC-Taiwan High Speed Rail Corporation began trial revenue operation with half-price fares starting on January 5 2007 and then launched official operation with regular fares on February 1. The intertemporal development pattern, that is the focus of this paper, has not played a big role in Taiwan HSR's deployment which has not involved multiple phases when starting operation.

South Korea's HSR system, Korean Train eXpress (KTX), also largely fits the "exclusive corridor" scenario (Park and Ha, 2006). The Gyeongbu Line connects Seoul, the capital city and the largest metropolis of the country, and Busan, the second-most populous city and the economic center of southeastern Korea. The line underwent two phases of construction. The first phase connecting Seoul and Daegu, the third largest metropolitan area after Seoul and Busan, started operation in 2004. The second phase, the Daegu-Busan section, went into service in 2010. The Honam Line also originates from Seoul (sharing facility with Gyeonbu Line in the Seoul-Osong section), with the other endpoint being Mokpo located at the southwestern tip of the Korean Peninsula. The Korean HSR development pattern has two characteristics. First, its main goal is to connect the rest of the country with Seoul. On September 1, 2010, the South Korean government announced a strategic plan to reduce travel times from Seoul to 95% of the country to under 2 hours by 2020. Second, some intertemporal patterns exist in the Korean case. In particular, sections of the same HSR line started operation sequentially, securing the service to the most important city as soon as possible.

So far Japan has 7 main HSR lines (Fu et al., 2014). The first Japanese HSR line, the Tokaido Shinkansen, opened in 1964 between Tokyo and Osaka, the two main metropolitan areas of the country. The second line, Sanyo Shinkansen, connects Osaka with Fukuoka, the two largest cities in western Japan and it is a westward continuation of the Tokaido Shinkansen. The Shin-Osaka to Okayama segment opened in 1972, while the remainder of the line opened in 1975. The Tohoku Shinkansen connects Tokyo with Aomori in Aomori Prefecture, running through the more sparsely populated Tohoku region of Japan's main island, Honshu, and will reach Sapporo by 2030. The Joetsu Shinkansen connects Tokyo and Niigata. It was merged with the existing Tohoku Shinkansen line at Ōmiya. The Hokuriku Shinkansen connects Tokyo with Kanazawa in the Hokuriku region of Japan. The first section, between Takasaki and Nagano in Nagano Prefecture, opened in 1997. The extension to Toyama in Toyama Prefecture and Kanazawa in Ishikawa Prefecture opened in 2015. Other than Honshu, Kyushu and Hokkaido, two of the four main islands of Japan, are also partially covered by HSR, which are connected with the HSR lines in Honshu. The Kyushu Shinkansen between the cities of Fukuoka and Kagoshima in Kyushu is an extension of the Sanyo Shinkansen. The two completed sections of the line opened in 2004 and 2011, respectively. The Hokkaido Shinkansen links up with the Tohoku Shinkansen in northern Aomori Prefecture in Honshu and continues on into the interior of Hokkaido through the undersea Seikan Tunnel. The initial Shin-Aomori to Shin-Hakodate-Hokuto section opened in 2016. Extension of the line to Sapporo is scheduled to open by March 2031. Although at a much larger scale compared with Taiwan and South Korea, Japan still exhibits the characteristics of “exclusive corridor”, with the center in Tokyo: new HSR segments either starts from Tokyo or immediately connects into another existing line connected to Tokyo. Therefore, there is no subnetwork developments as in China.

7. Concluding remarks

In this paper, we examine the development of the Chinese HSR network over the period 2003-2014. Our methodology relies on centrality analysis to identify changes over time in HSR network accessibility measured by node degree, strength, closeness, and betweenness.

Local analysis shows that sub-networks connecting regional centres, i.e., megacities, with second-tier cities are first built. Once such sub-networks are mostly established, they are also connected with each other. Moreover, a simultaneous rather than a sequential schedule for multiple HSR segment is at place at any particular time, further ensuring the amortization of the capital cost of construction equipment over a number of projects. This contribute to explain China's significantly lower HSR building cost compared with the other countries (Ollivier et al., 2014): relatively low labour cost, large scale of the HSR network, which has allowed the standardization of the construction elements, the development of technology capacity for equipment manufacturing and construction.

Global analysis confirms that the HSR network expands all the lower-elevation, more populous and prosperous regions. Consistently with literature, HSR has been found generally profitable in heavily travelled corridors between major population centres, while operations involving small population centres can struggle to cover their costs (Perl and Goetz, 2005). Although some clusters are critical politically, hence making the linkages relevant, HSR network development is still mainly driven by economic factors, which is reflected from the fact that nodes in the more economically vibrant regions present a higher number of routes passing through and higher service quality (i.e., lower travel time).

This paper is confined in a few ways. Our methodology heavily relies on the structure and physical layout of the HSR network, while some important dynamic features of the demand, such as the evolution of traffic and prices on different HSR routes are missing due to a lack of data. In other words, some critical operational patterns of the HSR network, such as the real usage of different connections of the system are unidentified. Some possible research venues can be implemented to include demand dynamics such as traffic and price. Future study should also focus on the connection between the Chinese

HSR network development and other critical demographic and economic changes (e.g., labour gravitation, formation of megalopolis) occurred in the Chinese society.

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References

Avenali, A., Bracaglia, V., D'Alfonso, T., Reverberi, P., 2018. Strategic formation and welfare effects of airline-HSR agreements. Mimeo.

Bai, Y., Feng, M., Jiang, H., Wang, J., & Liu, Y. (2015). Validation of Land Cover Maps in China Using a Sampling-Based Labeling Approach. Remote Sensing, 7(8), 10589-10606.

Barrat, A., Barthélémy, M., Pastor-Satorras, R., Vespignani, A., 2004. The architecture of complex weighted networks. Proceedings of the National Academyof Sciences, 101 (11), 3747–3752.

Campos, J., De Rus, G., 2009. Some stylized facts about HSR: A review of HSR experiences around the world. Transport Policy, 16(1), 19-28.

Cao, J., Liu, X.C., Wang, Y., Li, Q., 2013. Accessibility impacts of China's network. Journal of Transport Geography, 28, 12–21.

Cheng, Y. H., 2010. High-speed rail in Taiwan: New experience and issues for future development. Transport Policy, 17(2), 51-63.

China.com, 2016. China HSR: lucrative in east, loss-making in center and west. Available at: http://english.china.com/news/business/56/20160802/722066.html. Last retrieved: 24/08/2017

Chinadaily.com, 2018. Rail system to grow by 4,000 km in 2018. Available at: http://www.chinadaily.com.cn/a/201801/03/WS5a4bfb27a31008cf16da4b5c.html. Last retrieved: 10/04/2018

D'Alfonso, T., Jiang, C., Bracaglia, V., 2015. Would competition between air transport and HSR benefit environment and social welfare?. Transportation Research Part B: methodological, 74, 118-137.

D’Alfonso, T., Jiang, C., Bracaglia, V., 2016. Air transport and HSR competition: Environmental implications and mitigation strategies. Transportation Research Part A: Policy and Practice, 92, 261-276.

Erath, A., Löchl, M., Axhausen, K., 2009. Graph-theoretical analysis of the swiss road and railway networks over time. Networks and Spatial Economics, 9, 379–400.

Freeman, L.C., 1978. Centrality in social networks: conceptual clarification. Social Networks, 1, 215–239.

Fu, X., Oum, T. H., Yan, J., 2014. An analysis of travel demand in Japan's intercity market empirical estimation and policy simulation. Journal of Transport Economics and Policy, 48(1), 97-113.

Fu, X., Zhang, A., Lei, Z., 2012. Will China’s airline industry survive the entry of HSR? Research in Transportation Economics, 35(1), 13-25.

Garmendia, M., Ribalaygua, C., Ureña, J.M., 2012. HSR: implication for cities. Cities 29, 26–31.

Gutiérrez, J., 2001. Location, economic potential and daily accessibility: an analysis of the accessibility impact of the HSR line Madrid–Barcelona–French border. Journal of Transport Geography, 9(4), 229-242.

Jiang, C., D’Alfonso, T., Wan, Y., 2017. Air-rail cooperation: Partnership level, market structure and welfare implications. Transportation Research Part B: Methodological, 104, 461-482.

Jiang, C., Li, X., 2016. Low cost carrier and high-speed rail: A macroeconomic comparison between Japan and Europe. Research in Transportation Business & Management, 21, 3-10.

Jiang, C., Zhang, A., 2014. Effects of high-speed rail and airline cooperation under hub airport capacity constraint. Transportation Research Part B: Methodological, 60, 33-49.

Jiang, C., Zhang, A., 2016. Airline network choice and market coverage under high-speed rail competition. Transportation Research Part A: Policy and Practice, 92, 248-260.

Jiao, J., Wang, J., Jin, F., Dunford, M., 2014. Impacts on accessibility of China's present and future HSR network. Journal of Transport Geography, 40, 123–132.

Kim, H., Sultana, S., 2015. The impacts of HSR extensions on accessibility and spatial equity changes in South Korea from 2004 to 2018. Journal of Transport Geography, 45, 48-61.

Li, X., Jiang, C., Ma, J., Wang, K., 2018. Determinants of partnership levels in air-rail cooperation. Journal of Air Transport Management, 71, 88-96.

Lin, J., 2012. Network analysis of China's aviation system, statistical and spatial structure. Journal of Transport Geography, 22, 109-117.

Martin, J.C., Gutiérrez, J., Román, C., 2004. Data envelopment analysis (DEA) index to measure the accessibility impacts of new infrastructure investments: the case of the HSR train Corridor Madrid–Barcelona–French Border. Regional Studies, 38 (6), 697–712.

Newman, M.E.J. 2010. Networks: An Introduction. Oxford, UK: Oxford University Press.

Ng, A., Jiang, C., Li, X., O'Connor, K., Lee, P., 2018a. A conceptual overview on government initiatives and the transformation of transport and regional systems. *Journal of Transport Geography*, in press.

Ng, A., Wong, K., Shou, E., Jiang, C., 2018b. Geography and institutional change: The insight from a container terminal operator. *Maritime Economics and Logistics*, in press.

Ollivier, G., Sondhi, J., Zhou, N., 2014. HSRways in China: A Look at Construction Costs. China Transport Topics No. 9, World Bank.

Opsahl, T., Agneessens, F., Skvoretz, J., 2010. Node centrality in weighted networks: Generalizing degree and shortest paths. Social networks, 32(3), 245-251.

Park, Y., Ha, H. K., 2006. Analysis of the impact of high-speed railroad service on air transport demand. Transportation Research Part E: Logistics and Transportation Review, 42(2), 95-104

Perl, A.D., Goetz, A.R., 2015. Corridors, hybrids and networks: three global development strategies for HSR. Journal of Transport Geography, 42, 134-144.

Rothengatter, W., 2011. Competition between airlines and HSR. Critical Issues. In: Air Transport Economics and Business, Eds. Macario, R., van de Voorde, E. Routledge, Oxford, England.

Shaw, S.L., Fang, Z., Lu, S., 2014. Impacts of HSR on railroad network accessibility in China. Journal of Transport Geography, 40, 112-122.

SDG (Steer Davies Gleave), 2004. HSR: International Comparisons. Available at: http://test.ricerchetrasporti.it/wp-content/uploads/downloads/file_541.pdf. Last retrieved: 03/04/2018.

To, W. M., 2015. Centrality of an Urban Rail System. Urban Rail Transit, 1(4), 249-256.

UIC - International union of railways, 2017a. High speed lines in the world. Updated 3rd July 2017. Available at: http://uic.org/IMG/pdf/20170703_high_speed_lines_in_the_world.pdf. Last retrieved: 24/08/2017

UIC - International union of railways, 2017b. Data of High Speed passenger-km. Available at: http://uic.org/IMG/pdf/high_speed_passenger-km_20170615_.pdf. Last retrieved: 24/08/2017

Wan, Y., Ha, H. K., Yoshida, Y., Zhang, A., 2016. Airlines' reaction to HSR entries: Empirical study of the Northeast Asian market. Transportation Research Part A: Policy and Practice, 94, 532-557.

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.

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.

Wang, K., Xia, W., Zhang, A., 2017. Should China further expand its HSR network? Consider the low-cost carrier factor. Transportation Research Part A: Policy and Practice, 100, 105-120.

Wang, K., Xia, W., Zhang, A., Zhang, Q., 2018. Effects of train speed on airline demand and price: Theory and empirical evidence from a natural experiment. Transportation Research Part B: Methodological, 114, 99-130.

Xia, W., Jiang, C., Wang, K., Zhang, A., 2018. Air-rail revenue sharing in multi-airport system: Effects on traffic and social welfare. Working paper.

Xia, W., Zhang, A., 2016. HSR and air transport competition and cooperation: A vertical differentiation approach. Transportation Research Part B: Methodological, 94, 456-481.

Xia, W., Zhang, A., 2017. Effects of air and HSR transport integration on profits and welfare: the case of air-rail connecting time. Forthcoming on: Journal of Air Transport Management, 65, 181-190.

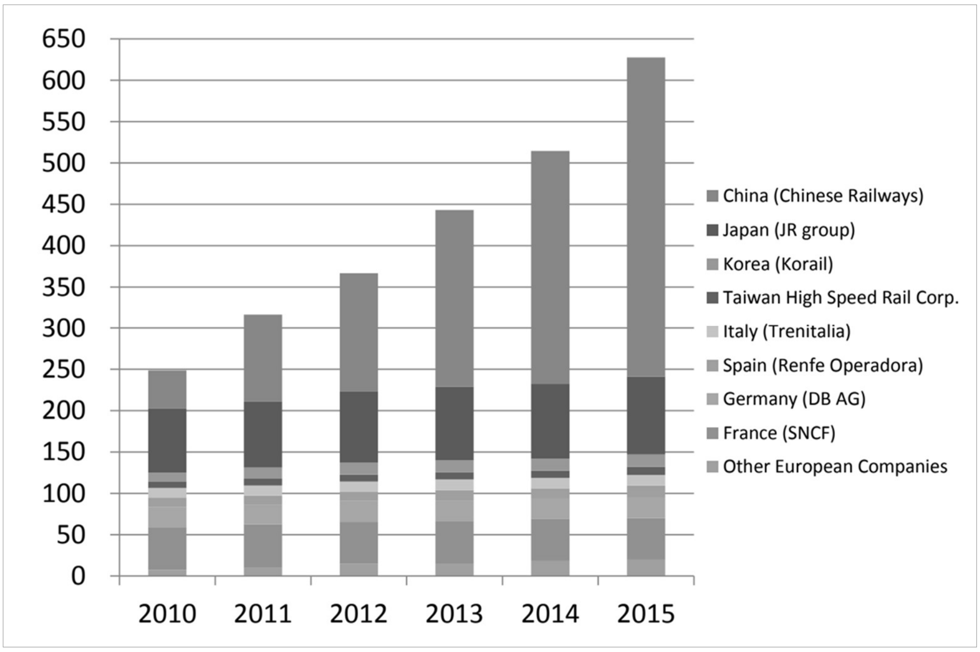
Yang, H., Zhang, A., 2012. Effects of HSR and air transport competition on prices, profits and welfare. Transportation Research Part B: Methodological, 46(10), 1322-1333.

Zhang, Q., Yang, H., Wang, Q., Zhang, A., 2014. Market power and its determinants in the Chinese airline industry. Transportation Research Part A: Policy and Practice, 64, 1-13.

Zhang, Q., Yang, H., Wang, Q., 2017. Impact of HSR on China's Big Three airlines. Transportation Research Part A: Policy and Practice, 98, 77-85.

List of Figures

Figure 1. HSR passenger-km



Source: UIC (2017b)

Figure 2. Total Length of Chinese HSR Tracks

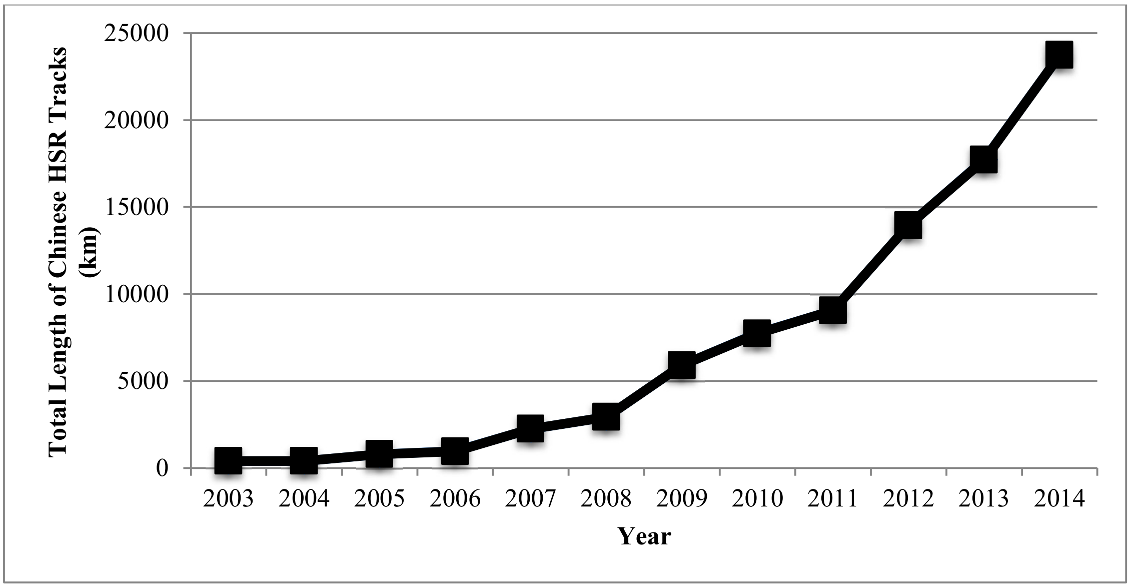


Figure 3. Distribution of Node Degrees

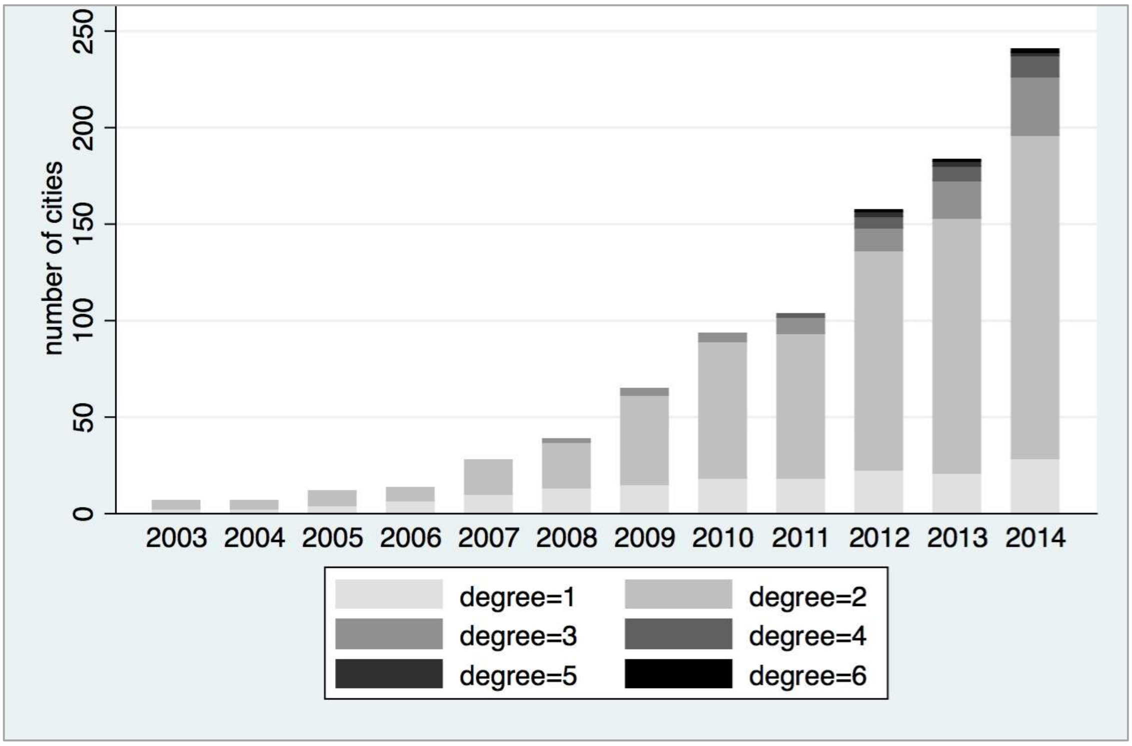
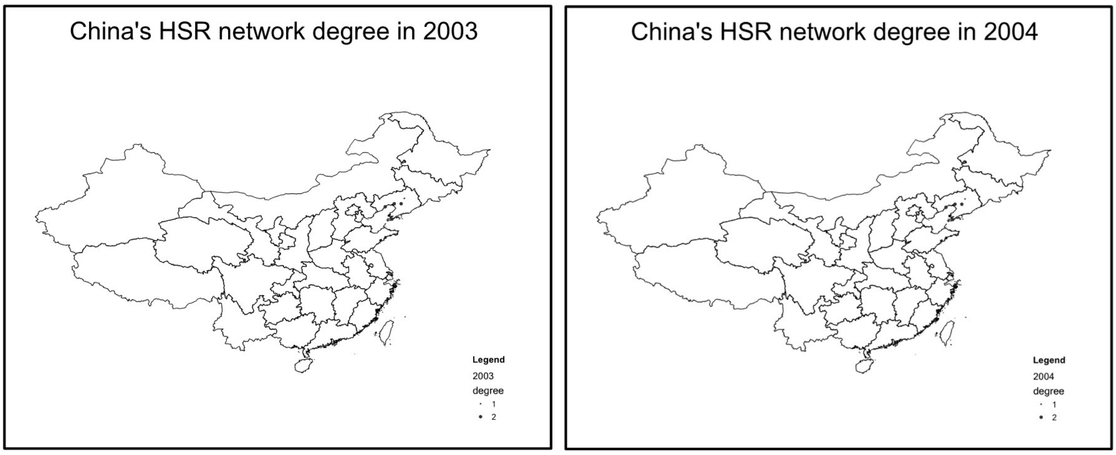
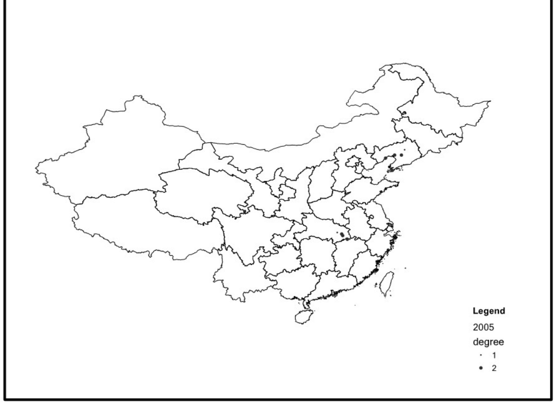
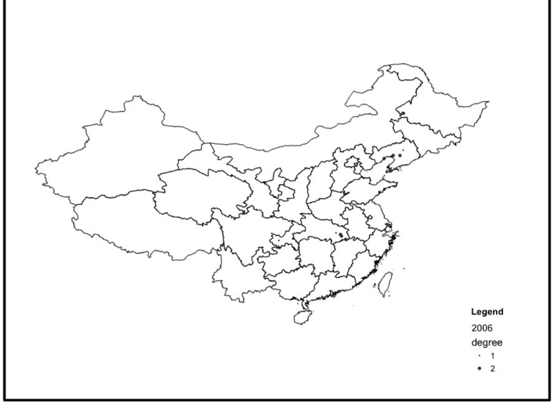
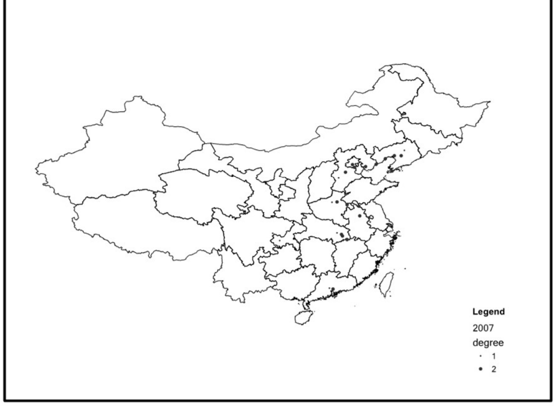


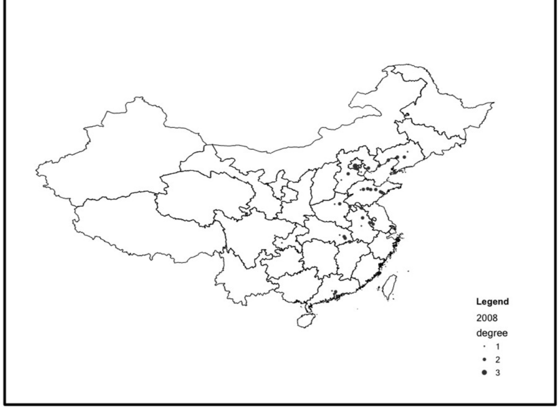
Figure 4 Node Degrees of the Chinese HSR Network

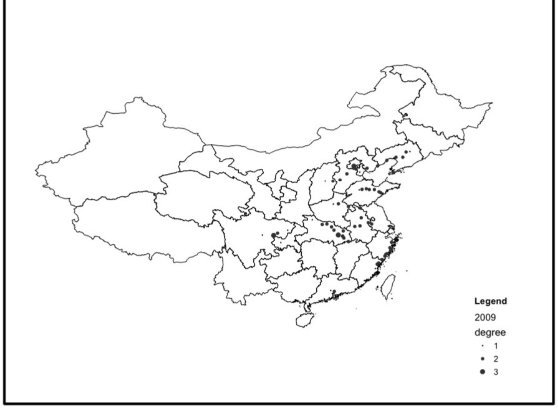


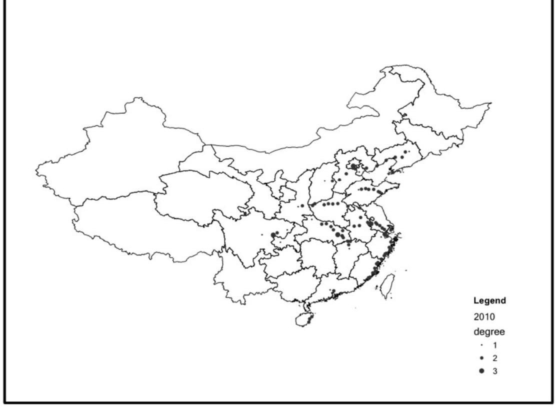

China's HSR network degree in 2005

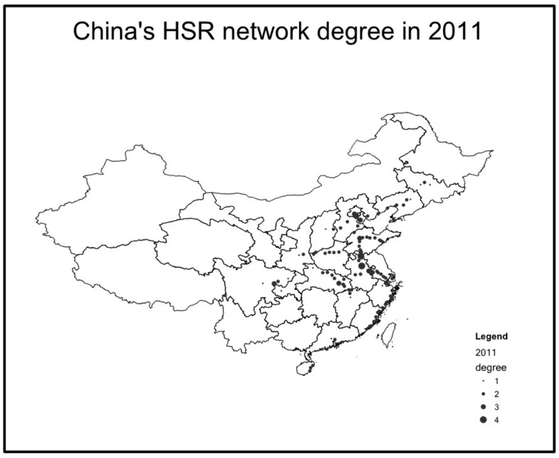

China's HSR network degree in 2006

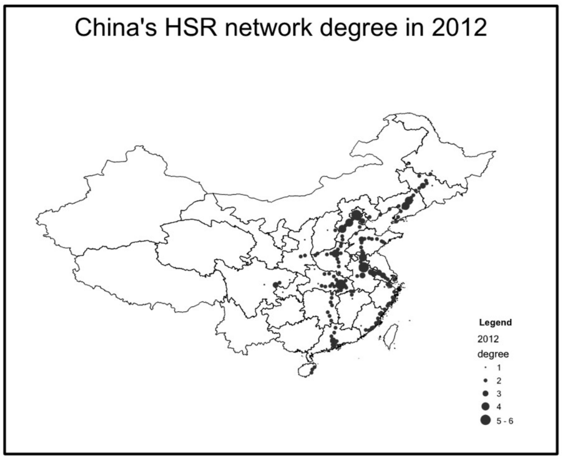

China's HSR network degree in 2007

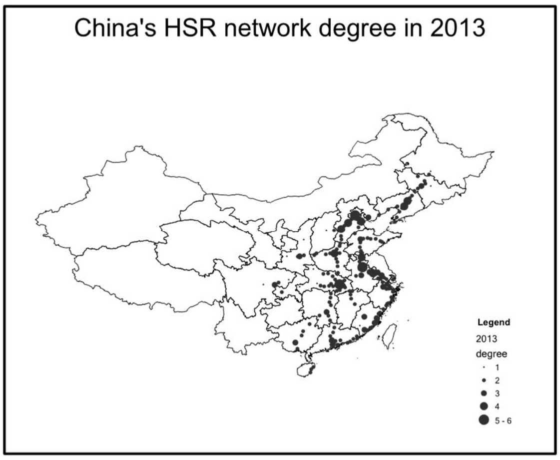

China's HSR network degree in 2008


China's HSR network degree in 2009


China's HSR network degree in 2010







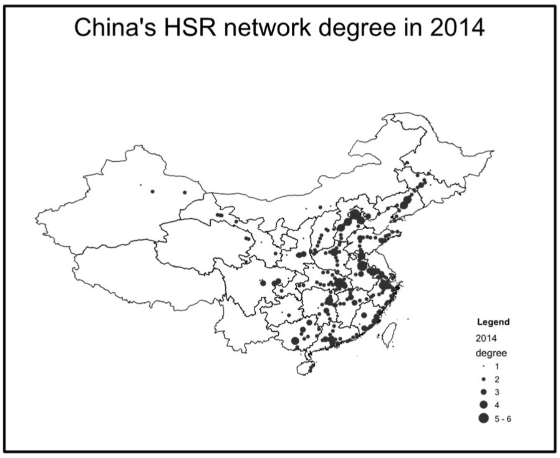
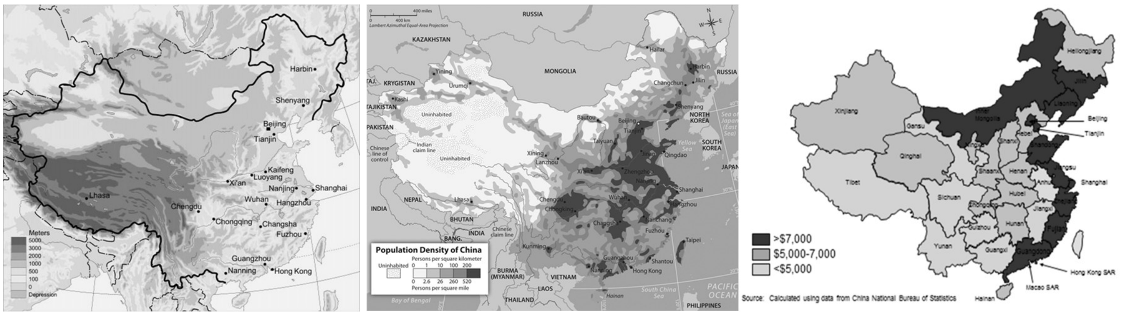


Figure 5 China's Topology (A), Population Density (B) and Per-capita GDP (C)



(A) (B) (C)

(A) Source: https://depts.washington.edu/chinaciv/geo/land.htm
(B) Source: http://future-economics.net/2015/02/17/internal-chinese-geopolitics/
(C) Source: http://www.fas.usda.gov/sites/default/files/2014-04/china_iatr_5.png

Figure 6 Node Strength of the Chinese HSR Network

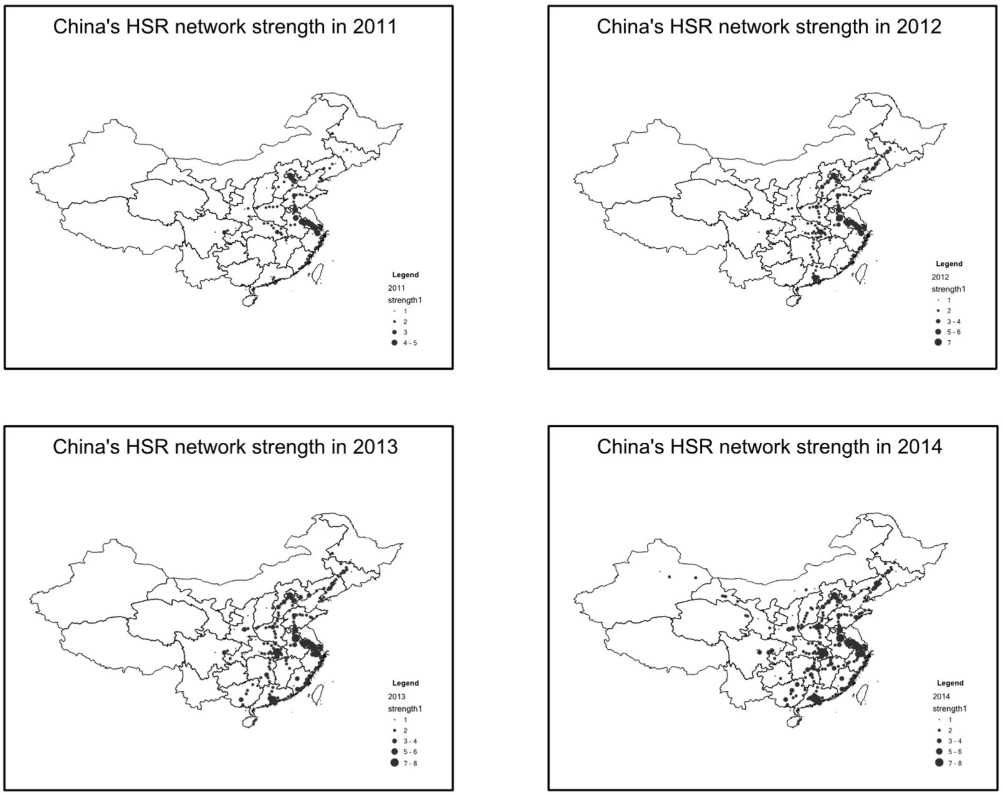
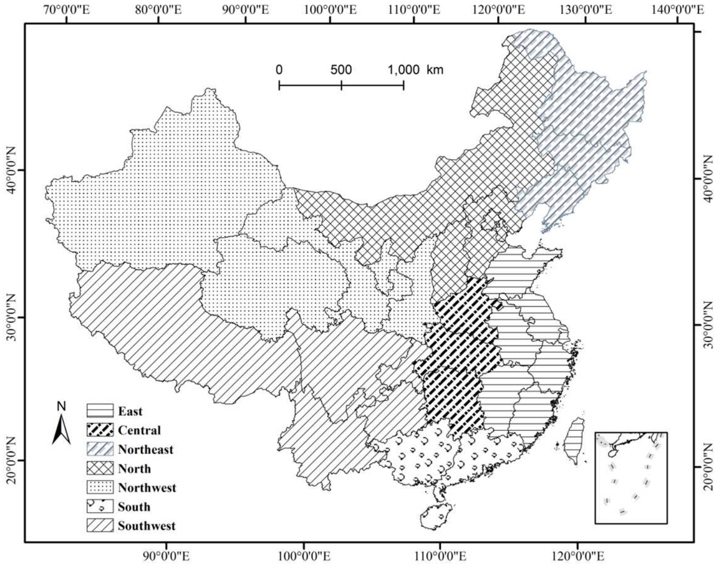


Figure 7 Geographical locations of regions and provinces in China



Source: Bai et al. (2015)

Figure 8 HSR System in East Asian countries

Source: Adapted from https://en.wikipedia.org/wiki/High-speed_rail_in_East_Asia. Last retrieved 10/04/2018

List of Tables

Table 1 Yearly Ranking of Average Closeness Centralities by Regions

Year/Rank	2014	2013	2012	2011	2010	2009	2008	2007
1	C	C	A	A	B	B	B	B
2	D	A	D	C	C	A	A	A
3	A	D	B	B	A	C	C	C
4	E	B	C	D	D	F	D	D
5	B	E	E	F	F	D	E	E
6	F	F	F	E	E	E	F	F

*A: North China; B: Northeast China; C: East China; D: Central China; E: South China; F: Southwest China

Table 2 Yearly Ranking of Average Betweenness Centralities by Regions

Year/Rank	2014	2013	2012	2011	2010	2009	2008	2007
1	D	D	A	A	D	A	A	A
2	C	C	D	C	C	B	B	B
3	B	A	B	D	A	C	D	C
4	A	B	C	B	B	D	C	D
5	E	E	E	F	F	F	E	E
6	F	F	F	E	E	E	F	F

*A: North China; B: Northeast China; C: East China; D: Central China; E: South China; F: Southwest China