Graph-theoretical analysis of the Chinese High Speed Rail Network over time

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LONG-DISTANCE PASSENGERS TRANSPORT: MARKET, PLANNING, INNOVATION

TRASPOL

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Background (1/2)

- **High-speed rail** (HSR) has been a **focal element** of transport policies in many countries. Investments in HSR pursue various goals: **relief of congestion on conventional rail, road or air networks**, catalysis of **economic development and integration**, as well as **restraint of the environmental impact of the transport industry**.

- Literature tried different classifications of HSR models according to the **level of integration with the rest of the network, speed and type of services** and also **track pricing** (Beria and Grimaldi [2017] summarizes the main concepts)

- Certain **attributes** have experienced more success than others: HSR is **generally profitable in heavily traveled corridors of 300–800 km between major population centers**, while **in longer distance operations involving smaller population centers can struggle to cover their costs**.

Background (2/2)

- **Perl and Goetz (2015)** builds upon the categorizations developed by Givoni (2006) and Campos and de Rus (2009) by considering not only train and track compatibility, speed, and cost, but also factors such as the **geographic scope of development** (corridor, national, continental), and **network configuration** (trunk lines, bridge lines, radial, decentralized):

  - **exclusive corridors**, between megacities of more than 10 million inhabitants (e.g., in Japan),
  - **hybrid networks**, made of new HSR links connecting conventional rail lines, which remain crucial, multiplying the number of origins and destinations to be served (e.g., in France);
  - **comprehensive national networks**, with new infrastructure linking all major and mid-sized communities across the country (e.g., in Spain and China).

Literature and Gap (1/2)

- Evaluations of profitability of these models yield outcomes that range from **generally positive assessments of the corridor and national hybrid models** to **more uncertainties about the international hybrid and comprehensive national network models** (Perl and Goetz, 2015)

- Also, transport literature on HSR development ubiquitously focus on
  - the **static analysis** of its impact on accessibility (e.g., Gutiérrez et al., 1996; Gutiérrez, 2001; Ortega et al., 2015), or
  - the **relationship between this impact and economic development/integration – ex ante or ex post** (e.g., De Rus and Nombela, 2007; Fröidh, 2005; 2008; Adler et al., 2010; Leheis, 2012).

- A vast branch of literature focuses on the **impact of intermodality between HSR and other modes of transport**, mainly air transport (Albalate et al., 2014; D'Alfonso et al., 2015, Yang and Zhang, 2012)

Literature and Gap (2/2)

- However, no literature has ever attempted to **map over multiple years the development of HSR network models**.

- The **pattern of the development** rather than the structure of the HSR system might play a critical role in **building a competitive advantages**.

- We try to fill this gap by **examining the development pattern of a pivotal example** of **comprehensive grid network, the Chinese High Speed Rail Network (CHSRN)**

Case study

- The CHSRN (**the largest in the world**) covers 23,914 km and is **planned to cover 12,255 km**, with **10,730 km of lines already under construction** (UIC, 2017).

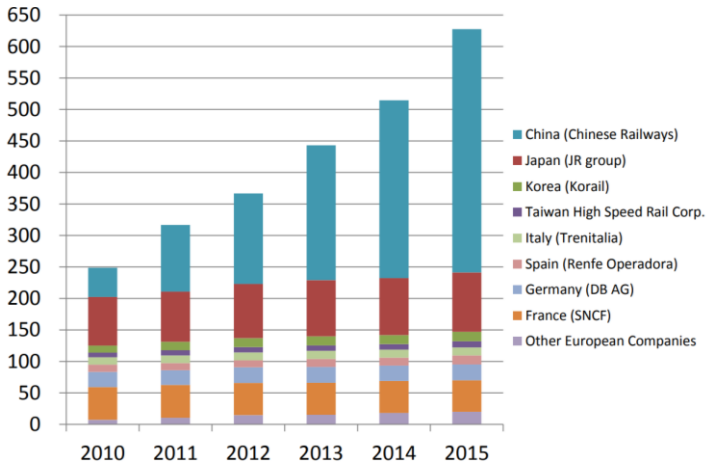


Figure 1 DATA of High Speed passenger-km (billion)

- China has been driving the growth of HSR traffic in the period 2013-105

- The CHSRN has been built at a **unit cost compared at most two-thirds of that in similar projects in other countries** (Ollivier, 2014).

- **Performance seems closely related to population/economic strength of cities HSR serves.**
  - The CHSRN started to make a profit in the east (China.com, 2016) connecting mega cities in populated areas with strong economies. Conversely, services running through the central and western regions are still far from breaking even.

Methodology

- We make use of graph theoretical tools. The HSR network is described as an **oriented graph** $G = (n, e)$ where
  - n is the set of nodes (HSR stations)
  - e is the set of edges (HSR lanes)

- We use different concepts **of node centrality in weighted networks** (Opsahl et al., 2010), to measure and rank the connectivity of different cities with HSR stations over years:
  - Closeness
  - Betweenness
  - Degree
  - Strength

- We share the methodology in Erath et al. (2009), which investigates the development of the **Swiss road and railway network** during the years 1950–2000

- Applications in other network industries, e.g., **air transport** (e.g., Burghouwt and Redondi, 2009; Malighetti et al., 2013)

Dataset

- We focus on years 2003-2014
  - In 2003, the **Qin-Shen Passenger Designated Line (PDL)**, connecting Qinhuangdao and Shenyang in northern China, has been opened for use (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 CHSRN (Ollivier et al., 2014).**

- We incorporated **upgraded existing lines that meet speed standards** of HSR into our analysis

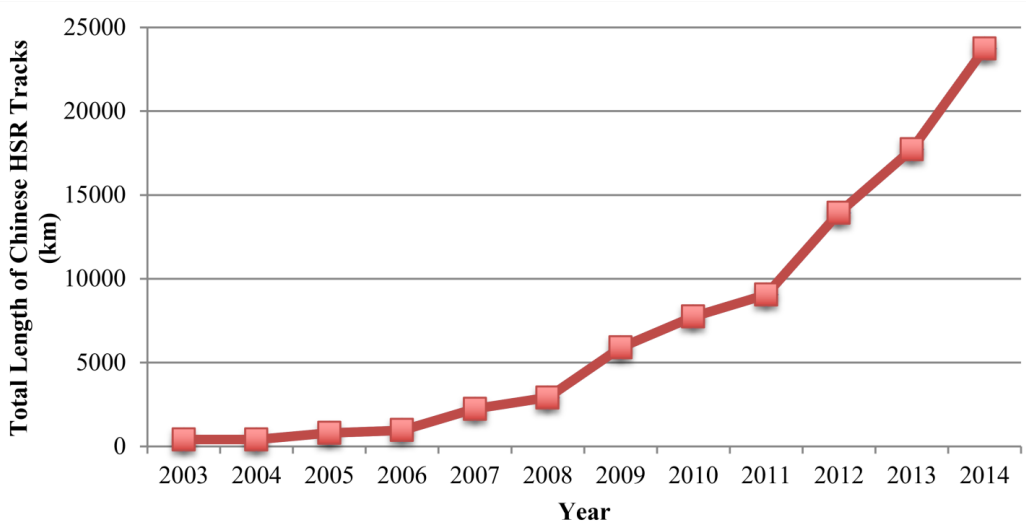


Figure 2 Total Length of Chinese HSR Tracks by Year

- From 2003 to 2007 the growth of HSR track length was relatively slow
- Starting from 2008, the growth gained a substantially higher momentum. Higher speed of growth after 2011, causing the total length of HSR tracks to more than double within 3 years.
- This was be partially driven by the **financial crisis unveiled in 2007-2008**. With a weakened global demand, China relied on investment for GDP growth.
- **Stimulus program** (US$ 586 billion) for infrastructure development (CHSRN is among one of the biggest beneficiaries)

Node degree and strength

- **Node Degree** counts how many nodes are connected directly to the focal node in a network.

$$k_i = C_D(i) = \sum_j^N x_{ij}$$

$i \in n$ focal node

$j \neq i, j \in n$ all other nodes,

N is total number of nodes (cardinality of n)

$$x_{ij} = \begin{cases} 1 \; if direct \; connection \; exists \; between \; node \; i \; and \; node \; j \\ 0 \; otherwise \end{cases}$$

- **Node Strength** is a generalization of degree in weighted networks analysis. Weights are to indicate how strong an edge between two nodes is.

$$s_i = C_D^w(i) = \sum_j^N w_{ij}$$

w_{ij} weight of edge connecting node i and node j

For non-social networks, **the strength often reflects the operational performance of edges**. Weight measures are:

(1) number of different HSR routes passing two nodes

(2) train service class

(3) distance

(4) speed

(5) travel time

Node degree (1/3)

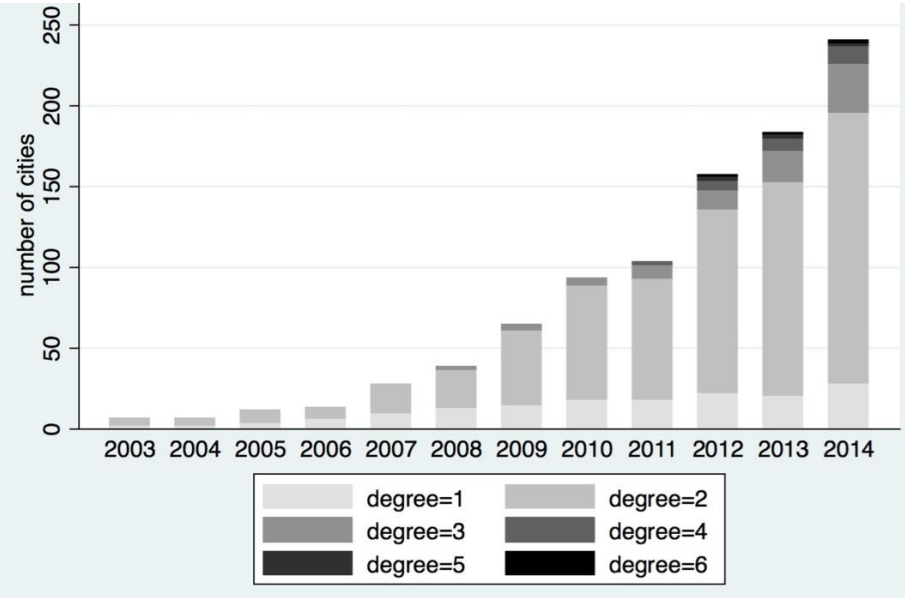


Figure 3 Distribution of Node Degrees across Years

- In the period 2003-2010 there is a **rapid increase of nodes with lower degrees.** Then, **nodes with higher degrees emerge**
- **Sub-networks that connect regional centers with second-tier cities nearby are fist built.** Once these sub-networks are mostly established, **they are also connected with each other, which eventually link the farther-away regional centers.**

- Once sub-networks are built, connections between a regional center and a second-tier city within another region, might become economically viable
- Exploitation of **economics of density** deriving from **connections between two sub-networks**, which **eventually connect the farther-away megacities**

Node degree (2/3)

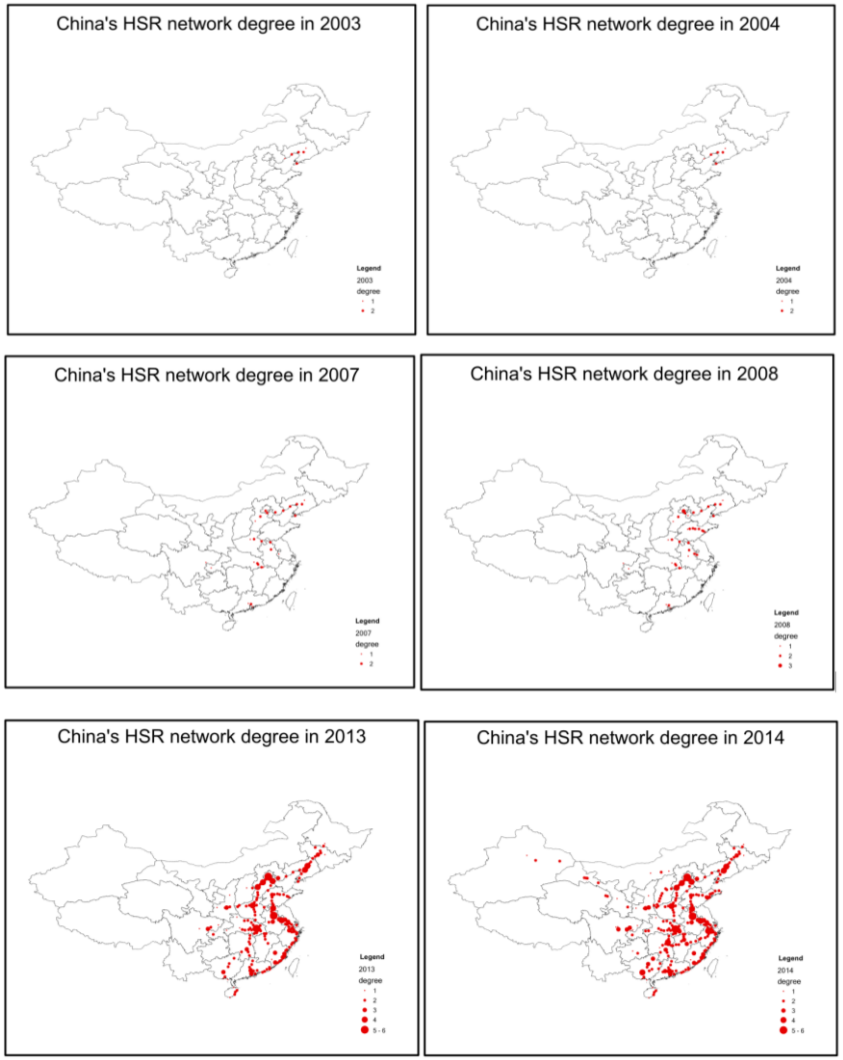


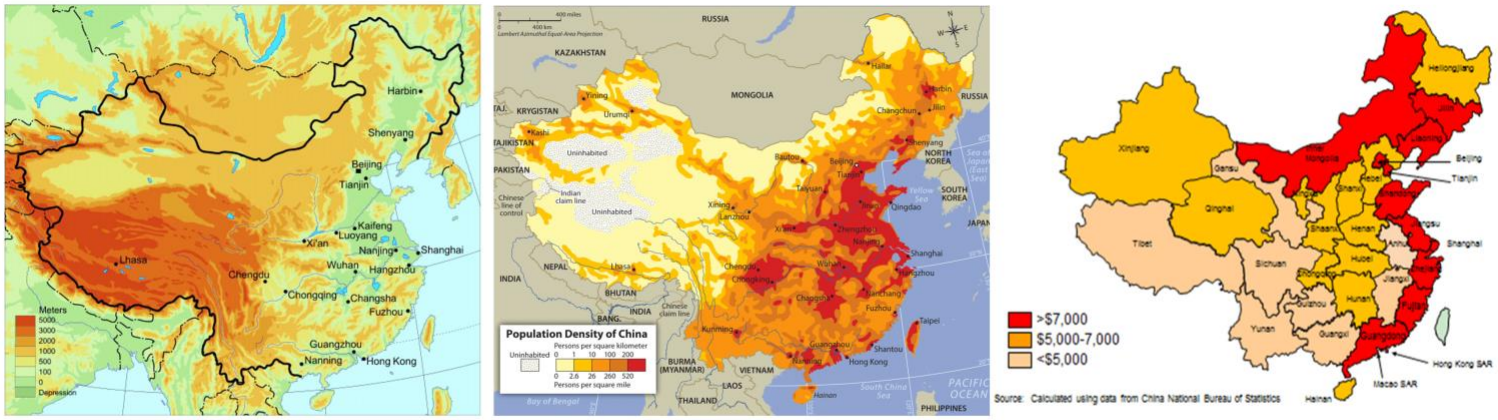
Figure 4 Node Degrees of the Chinese HSR Network by Year

- A **simultaneous instead of sequential schedule for multiple HSR segments is in place at any particular time**, further ensuring **lower cost thanks to economies of scale in development**.

- Major driving forces for **China's significantly lower HSR building cost** compared with the other countries other than those already mentioned in the literature (Ollivier, 2014):

    - relatively **low labour cost**
    - **standardization** of the construction elements
    - **development of technology capacity (learning economies)** for equipment manufacturing and construction
    - **amortization of the capital** cost of construction equipment over a number of projects

Node degree (3/3)



(A) (B) (C)

Figure 4 China's Topology (A), Population Density (B) and Per-capita GDP (C)

- We find that the CHSRN network expands **all the lower-elevation, more populous and more prosperous regions of China but leaves out the other regions**.
- Besides, the CHSRN system started to develop **from the northern part due to political, geographical and demographic reasons.**
- However, starting from 2013, the CHSRN system started to develop in **Central China and East China, thanks to their more central**

Strength

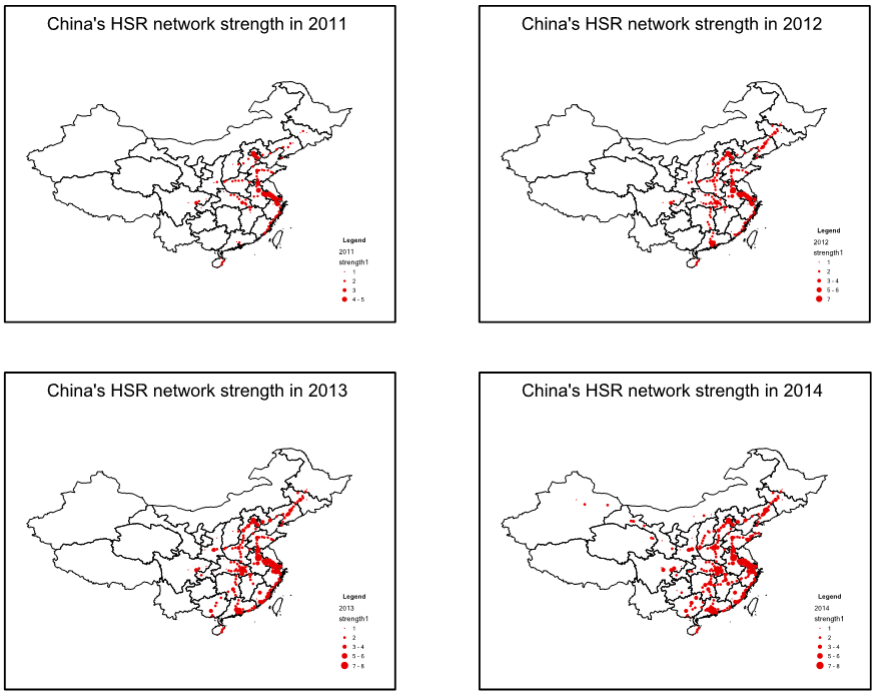


Figure 5 Node Degrees of the Chinese HSR Network by Year (weight := number of different HSR routes passing two nodes).

- The **northern cluster** (around Beijing) becomes less significant while the **eastern cluster** turns out to be more noteworthy in terms of **strength rather than degree**.
- Besides, the **southern cluster, with lower degree, assumes relatively higher strength.**
- These differences probably suggest that **although the northern cluster around Beijing is critical politically**, hence making the linkages very important, **the level of HSR service is still mainly driven by economic factors**, which is reflected from the fact that **the more economically vibrant delta regions have more routes passing through**.
- Results are confirmed with other weights (e.g., speed, travel time)

Node closeness and betweenness (1/2)

- **Node Closeness** is a measure of centrality in a network which calculates **how adjacent a focal node is to all other nodes in the network**

$$C_C^{w*}(i) = \sum_j^N [d^w(i,j)]^{-1}$$

with

$d^w(i,j)$ is the shortest generalized distance

$$d^w(i,j) = min(\frac{1}{w_{ih}} + ... + \frac{1}{w_{hj}})$$

- **Node Betweenness** measures the number of shortest paths that cross a node. A node with higher betweenness would have more control over the network, because more routes will pass through that node.

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

with

$g_{jk}^w(i)$ is the number of shortest paths that cross node (i)

$g_{jk}^w(i)$ is the number of shortest paths that connect node (j) and (k)

Node closeness and betweenness (2/2)

- Since it is burdensome to make comparisons on city level, we divide China into a few geographical regions and then rank these regions across years by average closeness and betweenness

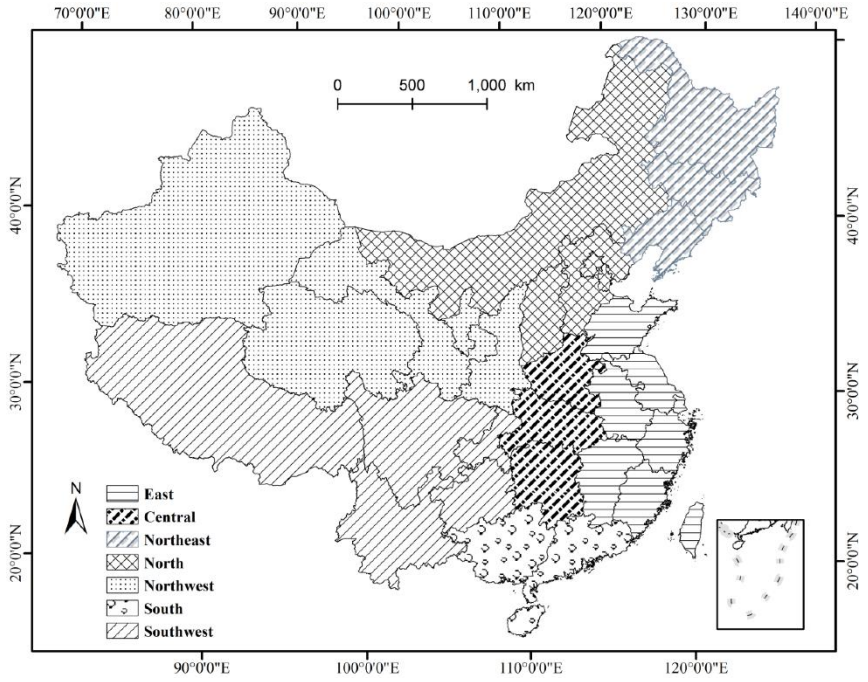


Figure 6 Geographical locations of regions and provinces in China

- **Northwest China** is not in the rank due to the fact that the Northwest sub-network was not linked to other sub-network until 2014, **while closeness and betweenness can be compared sensibly only within a large network**.

Node closeness and betweenness (2/2)

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

- The **CHSRN started to develop from the northern-east cluster** due to political, topological and demographic reasons.
- From 2013, the **Central Cluster** and the **Eastern Cluster** show higher closeness and betweenness due to **geographical and economical reasons**.
- However, the **Central Cluster** has been acquiring **more control over the network** (**higher betweenness**)

Conclusions and Shortcoming of the work

- We have identified the **temporal pattern of the development of the CHSRN** highlighting political, economical, demographical and topological reasons.

- We have identified possible technical rationales which can explain the lower unit cost (i.e., **simultaneous instead of sequential schedule for multiple HSR sub-cluters**, which may potentially drive **economies of scale, economies of density, learning economies)**

- Our methodology relies on the **structure and physical layout** of the CHSRN, while some important dynamic features, such as the **traffics and the prices** on different routes **are missing** due to a lack of data sources. In other words, **some critical operational patterns of the CHSR, such as the real usage of different parts of the network, are unidentified.**

Q&As

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