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Address GIZ in China:

Tayuan Diplomatic Office Building 2-5
14 Liangmahe South Street, Chaoyang District
100600 Beijing, P. R. China
T +86 (0)10 8527 5589
F +86 (0) 10 8527 559
E info@giz.de
I www.giz.de
I www.transition-china.org/mobility

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Responsible:

Alexander von Monschaw, GIZ in China
alexander.monschaw@giz.de

Authors:

OU Xunmin, Associate Professor, Tsinghua University
YUAN Zhiyi, PhD Candidate, Tsinghua University
WANG Yanzhe, Masters Candidate, Tsinghua University
REN Lei, PhD Candidate, Tsinghua University

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List of Abbreviations

BMDV	Ministry for Digital and Transport of the Federal Republic of Germany
CNY	Chinese Yuan
CO_2	Carbon Dioxide
CRC	China Railway Corporation
CREC	China State Railway Group
DID	Difference-in-Difference Methodologyv
EV	Electriv Vehicles
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HSR	High-speed Rail
LCA	Lifecycle Analysis
MFS	Sino-German Cooperation on Mobility and Fuels Strategy
MoT	Ministry of Transport of the People´s Republic of China
NDRC	National Development and Reform Commission
NRA	National Railway Administration
R&D	Research and Development
TOR	Train Occupancy Rate
UIC	International Union of Railways

◆ Executive Summary ◆

In recent decades, the high-speed rail (HSR) network in China has witnessed extraordinary growth.[1] In 2003, the inauguration of the passenger train between Qinhuangdao and Shenyang signaled the era of HSR intercity transportation, reflected in comprehensive planning under the leadership of China Railway Corporation (previously Ministry of Railways) in 2004. The *Medium and Long-Term High-Speed Railway Network Planning* (revised in 2008) for the first time proposed a country wide HSR corridor featuring four vertical and four horizontal axes by 2020. An updated planning from 2016 raised the envisioned HSR lines to eight vertical and eight horizontal corridors by 2030. In 2020, the *Outline of Powerful Nation Railway Advance Planning in the New Era* put forward the goal of full access to HSR lines for cities with at least 500,000 inhabitants.

Preliminary findings show that the HSR expansion has significantly contributed to people's mobility choices, it has strengthened intercity relations and benefitted the socio-development. Meanwhile, its negative impacts on China's environmental footprint should be taken into consideration as well.

Commissioned by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in the frame of the project "Sino-German Cooperation on Mobility and Fuels Strategy (MFS)", the research group headed by Prof. Ou Xunmin from Tsinghua University conducted this study on the HSR development and respective policies in China. Based on a literature review, followed by an in-depth case study, various socio-economic and environmental impacts are assessed, including the quantification of modal shift from civil aviation towards high-speed trains and its CO_2 emission reduction potentials.

This report includes: 1) general introduction to the baseline, policy system, accessibility, passenger travel patterns, mobility cost and the socio-economic and environmental impacts of HSR; 2) macro-level calculation of the benefits of HSR-aviation substitution; 3) micro-level lifecycle analysis (LCA) of carbon emissions for the Beijing-Shanghai HSR connection as case study; 4) summary and policy recommendations on future HSR development.

The second and third chapter depict the core of this study. Chapter 2 employs the differences-in-differences (DID) methodology for a quantitative analysis of the substitution effect of HSR development on civil aviation in China. Main findings include:

1) Based on the operations of the network featuring four vertical and four horizontal corridors, the introduction of HSR significantly reduces the air passenger volume. In general, the number of flights and passengers is lowered by 28.7 % and 31.8 % respectively in cities with HSR access; the modal shift from civil aviation towards HSR can hence have a positive impact on the decarbonisation of the transportation sector.

2) In comparison with other means of transport, the competitive advantage of HSR depends largely on travel duration, with largest effects for journeys of less than four hours, where the number of flights and passengers are cut by 74.2 % and 82.5 %, even resulting in cancellation of certain flight routes. There remain further competitive advantages for travel durations up to six hours, equaling a travel distance of 1,400 km.

3) The planned eight vertical and eight horizontal corridors will cover another 69 airports, compared to the previous four corridor planning, competing with an additional 834 air connections. The expansion of HSR-lines will have substitution effects on civil aviation of 8.8 %, which further rises by 0.7 % when considering the planned speed acceleration of railway corridors along the Yangtze River and the coast.

4) Once all cities with a population over 500,000 inhabitants are covered by the HSR network, HSR lines could reach almost all domestic airports. Estimations foresee that 26.2 % of all existing domestic passenger flights will be replaced by HSR travel.

Chapter 3 utilises a life cycle analysis (LCA) for the modelling and calculation of energy consumption and greenhouse gas (GHG) emission per unit of service (pkm) of the Beijing-Shanghai HSR line throughout its lifecycle, which indicates:

1) The energy consumption and GHG emissions in the lifecycle of the Beijing-Shanghai line are 0.4 MJ/pkm and 0.04 $kgCO_{2e}$/pkm respectively.

2) HSR entails significant benefits for energy conservation and emission reduction with emissions per unit of service being 0.10, 0.24, 0.26, 0.32 and 0.38 times that of airplanes, petrol- and diesel cars, electric vehicles (EV) and buses, respectively.

[1] Liu Lu. Impact Study of High-Speed Rail on Civil Aviation in China. Beijing: Beijing Jiaotong University, 2018.

3) A cleaner electricity supply and full-load passenger rate can further enhance the energy-saving and emission-reducing potentials of HSR travel.

Based on this study, it is thus recommended to advance HSR and strengthen the low-carbon developments of the transport sector. The HSR network should be expanded, vehicles should be modernised and a low-carbon electricity supply should be ensured. Based on an appropriate timetable design and higher capacity utilisation, the HSR's ecological advantages can hence be further expanded.

◆ Chapter 1 ◆

Introduction

1.1 Background

In recent decades, the high-speed rail (HSR) network in China has witnessed extraordinary growth, significantly improving and diversifying mobility options for the Chinese population. Whilst spatial and temporal connections between cities have been strengthened and the socio-economic development flourished, potential negative impacts of HSR expansion on the environment should be considered and analysed as well.

In the frame of the project "Sino-German Cooperation on Mobility and Fuels Strategy (MFS)" commissioned by the German Ministry for Digital and Transport (BMDV) in cooperation with the Chinese Ministry of Transport (MoT) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, the research group led by Prof. Ou Xunmin of Tsinghua University conducted the following study on the development of HSR in China. Based on a literature review and impact evaluation of HSR expansion on the transport sector, the study assesses its subsequent socio-economic as well as environmental impacts. In a concrete case study, the modal shift from civil aviation towards HSR and its carbon emission reduction effects are further calculated.

1.2 History and Planning

In 2003, the launch of the passenger train connecting Qinhuangdao and Shenyang unveiled China's HSR era of intercity rail transportation,[2] fulfilling the criteria of high-speed railway of International Union of Railways (UIC)[3] with a designed speed up to 250 km/h (300 km/h in certain segments). The detailed planning of HSR construction in China, headed by the China Railway Corporation (former Ministry of Railways) began in 2004, including the sixth major speed acceleration for railway lines in China. *The Medium and Long-Term High-Speed Railway Network Planning* (revised in 2008) proposed for the first time to build a HSR network featuring four vertical corridors including railway lines between Beijing-Harbin, Beijing-Shanghai, Beijing-Guangzhou and the Southeast coastal passenger line as well as four horizontal corridors including railway lines between Qinghai-Taiyuan, Shanghai-Wuhan-Chengdu, Shanghai-Kunming and Xuzhou-Lanzhou, stringing provincial capitals and more developed cities by 2020.[4] As part of this planning, the first full HSR line between Peking and Tianjin started operating in August 2008.

The Eleventh Five-Year Plan for the Development of Major Technical Equipment and Industrial Technology was passed by the National Development and Reform Commission (NDRC) in January 2008. The planning document promoted the localisation of engineering and construction, integrated human resources utilisation as well as environmental protection for HSR and common railway lines. A key area included further investments and strategic adaption of research and development (R&D) to accelerate respective innovation in the realm of manufacturing. Due to these funding policies, the HSR industry witnessed a significant economic boom.

Following on from previous transport planning, the State Council issued in 2012 the *Twelfth Five-Year Comprehensive Transportation System Plan*, which defined the comprehensive

[2] Liu Lu. Impact Study of High-Speed Rail on Civil Aviation in China. Beijing: Beijing Jiaotong University, 2018.
[3] *Dynastic History of Chinese High-Speed Railway – Demise of the First Qinhuangdao-Shenyang HSR*. [2011-06-11]. http:// finance.sina.com.cn/roll/20110611/00069974415.shtml.
[4] National Development and Reform Commission of China, *The Medium and Long-Term High-Speed Railway Network Planning* (revised in 2008). [2019-8-7]. https://www.ndrc.gov.cn/fggz/zcssfz/zcgh/200906/W020190910670447076716.pdf.

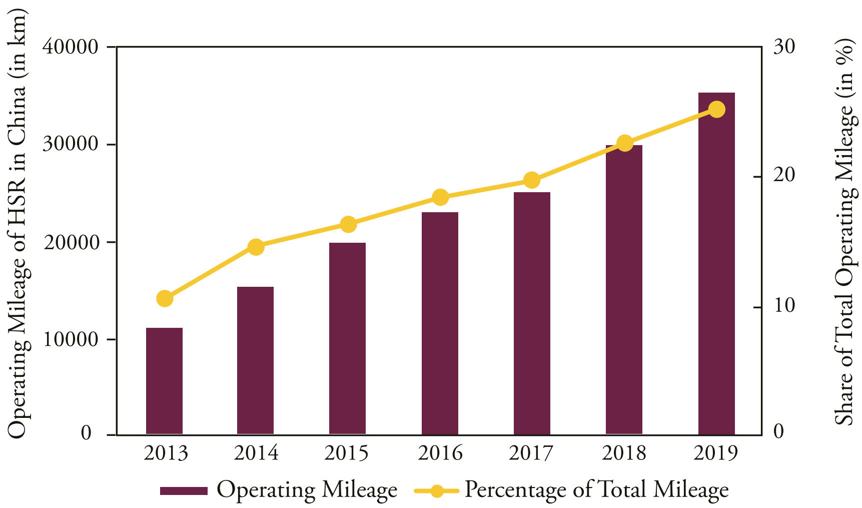
transportation network to feature "five vertical and five horizontal" corridors as the master frame, and 42 transportation hubs as the main nodes of the network.[5]

A 2016 revision of the Medium- and Long-Term Planning foresaw the increase up to eight vertical and eight horizontal corridors by 2030.[6] The set-up of a basic HSR grid was then already completed with the set-up of the HSR lines Shijiazhuang-Jinan and Peking-Shenyang-Harbin in 2018.

Since then, HSR has become an integral part of intercity passenger transportation in China, witnessing high growth rates for both passenger turnover as well as operating mileage. By 2019, the operating mileage of HSR had reached 35,388 km, equal to 2.2 times the mileage of 2013. Passenger turnover amounted to 774.67 billion pkm, equalling 2.6 times that of 2013 (see **Figure 1**) and accounting for 52.7 % of all pkm in 2019. In the same year, total ridership included 2.36 billion train rides, accounting for 64.4 % of the total passenger volume in railway transport.

By the end of 2020, the railway network of China had expanded to an operating mileage of 146,000 km, including 38,000 km of HSR lines.[7]

Figure 1 Operating Mileage and Passenger Turnover of HSR in China[8]



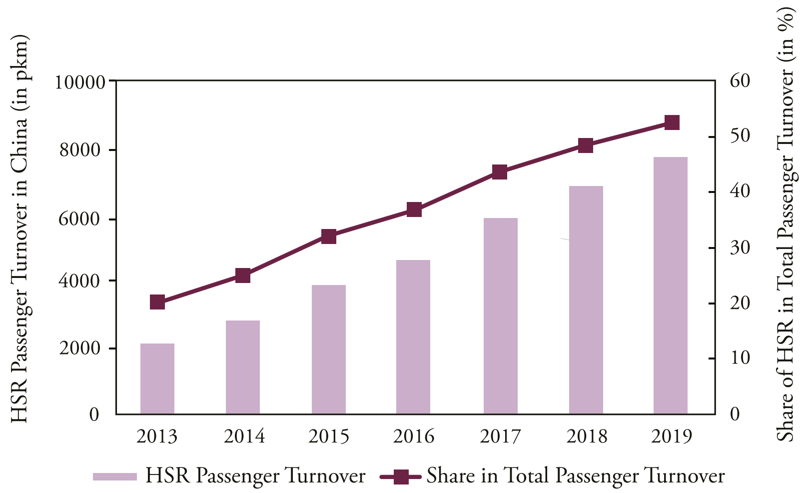
a) Share of HSR in Total Operating Mileage

[5] Ministry of Transport of the People's Republic of China. Twelfth Five-Year Plan: Transportation. [2011-04-13]. https://www. mot.gov.cn/zhengcejiedu/daoluyunshushierwughgyjd/xiangguanzhengce/201510/t20151014_1900816.html.

[6] National Development and Reform Commission of the People's Republic of China. Medium and Long Term Railway Network Planning. [2016-07-20]. http://www.gov.cn/xinwen/2016-07/20/5093165/files/1ebe946db2aa47248b799a1deed88144.pdf.

[7] Wu Jiatong. China Press | National Development and Reform Commission of China: *China Recorded an Operating Railway of 146,000 Kilometers by the end of 2020.* [2021-04-19]. http://news.china.com.cn/txt/2021-04/19/content_77419086.htm.

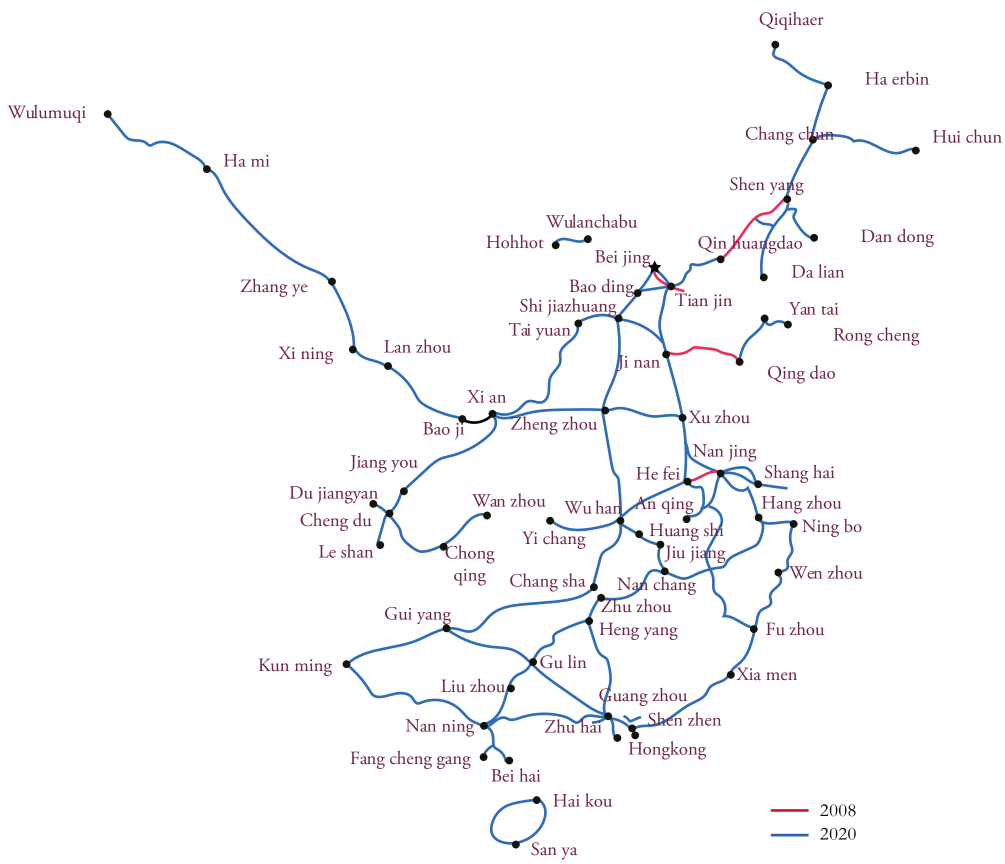
[8] National Bureau of Statistics of China. China Statistical Yearbook 2020. Beijing: China Statistics Press, 2020.



b) Share of HSR in Total Passenger Turnover

Figure 2 shows the evolution of HSR in China. The four vertical and four horizontal corridors started in the Eastern coastal provinces, whereas the HSR development in central and Western regions has long lagged behind. In terms of operating speed, key connections such as Beijing-Guangzhou and Beijing-Shanghai are designed with a maximum speed of 350 km/h, while the regional lines between Shanghai–Wuhan–Chengdu and the Southeastern coastal lines are capped at 250 km/h.

Figure 2 HSR Network in China (2008 vs. 2020) [9]



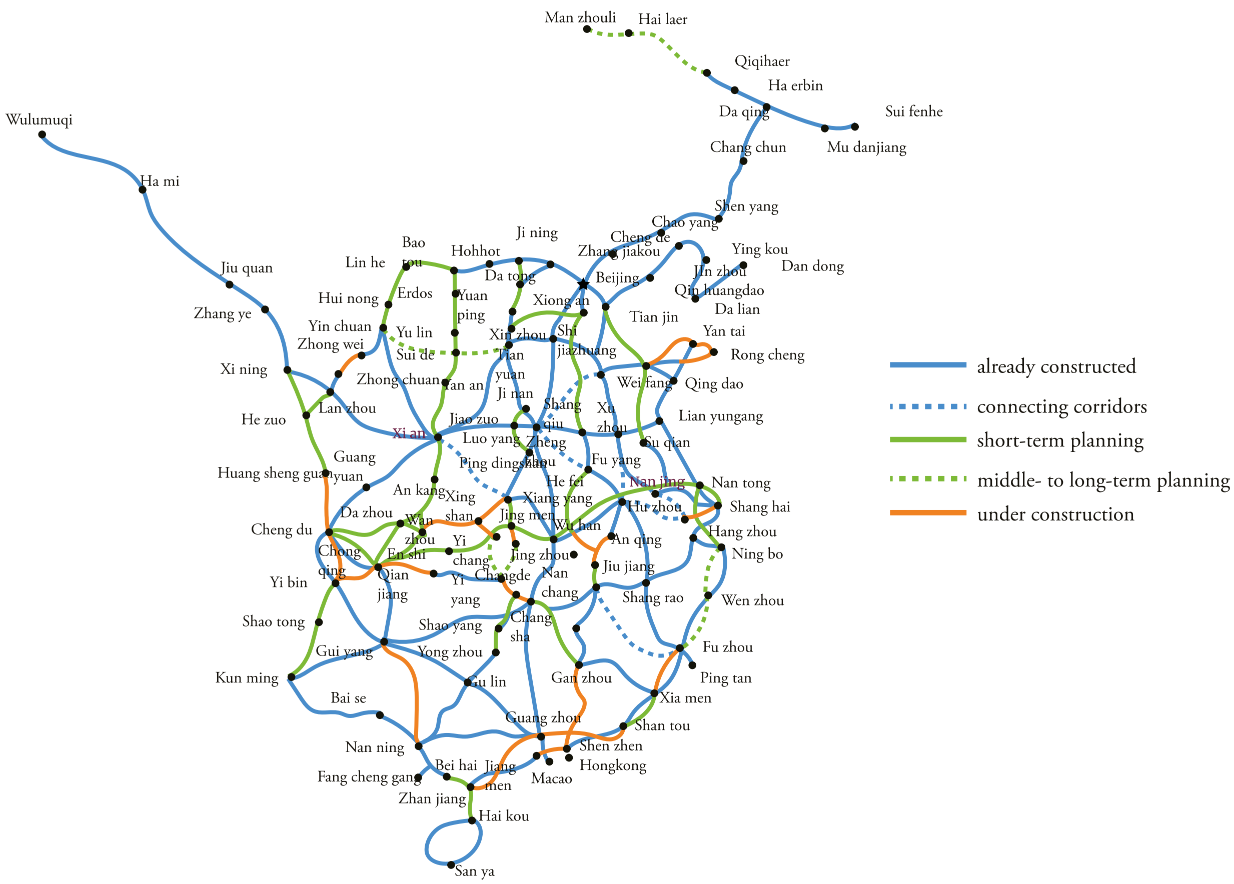
[9] Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. *China's High-Speed Rail Development. International Development in Focus.* Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

Figure 3 shows the ongoing eight vertical and eight horizontal corridors, including the North-South axes between Beijing-Shanghai, Beijing-Hong Kong (Taiwan), Beijing-Harbin/Beijing-Hong Kong-Macao, Hohhot–Nanning, Beijing-Kunming, Baotou (Yinchuan)-Haikou, and Lanzhou (Xining)-Guangzhou as well as the East-West axes between Suifenhe–Manzhouli, Beijing-Lanzhou, Qingdao–Yinchuan, the Eurasia Continental Bridge, Shanghai–Wuhan–Chengdu, Shanghai-Kunming, Xiamen-Chongqing and Guangzhou-Kunming. Based on these corridors, continuous integration of further intercity passenger lines and regional connections is planned. By September 2020, 70 % of the eight vertical and eight horizontal corridors had been completed, accessing almost all Chinese cities with a population over one million.

The *Outline of Powerful Nation Railway Advance Planning in the New Era* in 2020 set the HSR milestones for 2035 and 2050: HSR accessibility and city clusters within one, two and three-hour HSR travel circles for cities with a population over 500,000 inhabitants by 2035. [10] Capital cities of adjacent provinces should be reachable within three hours and major cities inside city clusters within two hours.

The continuous expansion of the HSR network has most recently been reinforced in the *Modern Comprehensive Transportation System for the 14th Five Year Plan*, issued by the State Council in January 2022.[11] According to the circular, the total operating mileage shall expand to 165.000 km in China by 2025, including 50.000 km of HSR lines.

Figure 3 HSR Planning in China: eight vertical and eight horizontal corridors (2016~2030)[12]



[10] The Central People's Government of the People's Republic of China [2020-08-13]. "200000 km, Planning Railway Power." Release of the Outline of the Advance Plan for Railway Power in the New Era. http://www.gov.cn/xinwen/2020-08/13/ content_5534553.htm.

[11] State Council of the People's Republic of China. [2022-01-18]. Modern comprehensive transportation system for 14th Five-Year Plan. http://www.gov.cn/zhengce/content/2022-01/18/content_5669049.htm.

[12] HSR Planning: 8 vertical +8 horizontal (2016~2030). https://www.sohu.com/a/446657295_682294.

1.3 Policies and Systems

1.3.1 Design Specifications and Technologies

The HSR policy framework in China includes macro-planning and construction designs. In 2013, the former Ministry of Railways, the main planning authority, split into the National Railway Administration (NRA) under the Ministry of Transport, and the China Railway Corporation (CRC), the state-owned company managing railway networks, which later changed its name to China State Railway Group Co., Ltd. (CREC). Most HSR infrastructure is built by joint ventures between central and provincial governments and private and state-owned enterprises.[13, 14] Since 2005, the speed levels of 250 km/h and 300 km/h for passenger railways proposed in the *Interim Regulations on the Design of New Passenger Railways with a Speed of 300-350 km/h* have been included in China's HSR landscape to apply to HSR construction norms.

China has organised the National Science and Technology Support Programs to encourage enterprises, universities, research institutes, key laboratories and engineering centres to further research and innovate in core HSR technologies.

1.3.2 Environmental Impact Assessment

Both the construction and operation of HSR lines pose considerable ecological risks and environmental impacts on the atmosphere and groundwater, noise levels as well as electromagnetics. Consequently, an Environmental Impact Report reviewed and approved by the National Development and Reform Commission is mandatory at the beginning of all HSR project cycles.

[13] China State Railway Group Co., Ltd. - About. http://www.china-railway.com.cn/gsjs/gsjj/.

[14] *Circular of the General Office of the State Council on Issuing the Provisions on the Main Responsibilities of the State Railway Administration, Internal Organizations and Staffing*. [2013-05-15]. http://www.gov.cn/zhengce/content/2013-05/15/content_7608.htm.

1.4 HSR Impact Analysis

1.4.1 Spatio-temporal Compression Effect

The burgeoning HSR development has delivered a series of impacts on cities and regions, and their underlying spatial structures. The influence on city level is mainly reflected in the spatial reconstruction of the affected HSR cities.[15, 16, 17]

The regional impacts of HSR connections are even more prominent, especially on the integrated development of city clusters and emerging metropolitan areas. By continuously dismantling geographic restrictions, HSR has increased the flow of production factors and blurred city borders, fostering cross-boundary urban integration[18] whilst depicting essential levers for rural urbanisation[19] and impacting regional development with restructured spaces and characteristics.[20,21,22,23,24]

1.4.2 Accessibility Enhancement

Accessibility is an important criterion for measuring the structure and layout of a transportation network.[25] For intercity travelers, HSR has shortened their journeys and satisfied their intercity demands for activities such as consumption and work, thus becoming a key means of transport in people's daily travels. Studies on the Beijing-Tianjin HSR found that the share of HSR in passenger transportation has reached 73 %, signaling a clear crowding out effect on other modes of intercity transportation.[26] Meanwhile, HSR development has led to overall higher travel frequency by train between neighbouring cities. In this context, the share of passengers travelling weekly or semiweekly on the respective HSR lines has increased, whereas less frequent travel patterns of only one or two commutes per semi-annum have steadily decreased.[27]

15 Chen Jianchang, Bao Jigang. *Tourist behaviour research and its practical significance. Geographical Research, 1988,* 7(3): 44-50.

16 Wang Degen, Chen Tian, Lu Lin, et al. *HSR effects and mechanisms of the spatial structure of regional tourism flow: a case study of the Beijing-Shanghai Railway. Acta Geographica Sinica,* 2015, 70(2): 213-232.

17 Givoni M, Banister D. Airline and railway integration. Transport policy, 2006, 13(5): 386-397.

18 Masson S, Petiot R. Can the high-speed rail reinforce tourism attractiveness? the case of the high-speed rail between Perpignan (France) and Barcelona (Spain). Technovation, 2009, 29(9): 611-617.

19 Guo Ningning, Yu Tao. Research Progress and Thoughts on the Spatial Effect of New HSR Cities. Modern Urban Research. 2018(8): 115-122.

20 Jiang Bo, Chu Nanchen, Wang Yuan, et al. Research Review and Prospect on HSR Impacts on Urban and Regional Space. Human Geography, 2016, 31(1): 16-25.

21 Hou Xue, Zhang Wenxin, LV Guowei, et al. Study on the impact of high-speed railway comprehensive transportation hub on surrounding areas -- Taking Beijing South Railway Station as an example. Urban Development Research, 2012, 19 (1): 41-46.

22 Wang Hao, Long Hui. On the influence of high-speed railway network construction on the spatial structure of urban agglomeration. Urban planning, 2009, 33 (4): 41-44.

23 Javier G. Location, economic potential and daily accessibility： an analysis of the accessibility impact of the high-speed line Madrid-Barcelona-French border. Journal of transport geography, 2001(9): 229-242.

24 Pol P M J. A renaissance of stations, railways and cities: economic effects, development strategies and organizational issues of European high-speed train stations. Delft: DUP Science, 2002.

25 Park Y, Ha H K. Analysis of the impact of high-speed railroad service on air transport demand. Transportation research part e: logistics and transportation review, 2006, 42(2): 95-104.

26 Hou Xue, Liu Su, Zhang Wenxin, et al. *HSR Behavioural Study Influenced by Beijing-Shanghai Inter-city Railway. Economic Geography,* 2011, 31(9): 1573-1579.

27 Wu Kang, Fang Chuanglin, Zhao Miaoxi, et al. *Spatial characteristics of cross-city mobility influenced by Beijing-Tianjin intercity HSR. Acta Geographica Sinica,* 2013, 68(2): 159-174. Zhang Xinsheng. *Research on Cross-city Commuters in City Integration. Nanjing University,* 2015.

1.4.3 Changes in the Transportation Market

The rapid evolution of HSR has reshaped the transportation market, especially road and aviation segments. In this context, a limited number of studies provides first analyses on the impact of HSR development on the transport sector.

By and large, HSR is the most competitive mode of transport within a travel range of approximately 150-800 km (equaling a travel time of three to four hours), whereas cars and buses are favoured for shorter journeys, and flights for longer trips, respectively.[28] Individual passenger behaviour is directly affected by factors of rentability, speed, comfort, convenience, and safety. Existing studies have found that the tipping points (where the probability of a different transport mode choice is high) of HSR against cars and planes are 152 km and 633 km. Meanwhile, highest modal shifts are reported in ranges of 100-300 km, 300-700 km and 700-1,000 km for buses, ordinary trains and aircrafts, respectively.[29,30,31] Another 2019 study also discovered that tipping points differ from city to city with a close correlation to per capita time value, the higher of which leads to greater passenger preference towards convenience and efficiency. [32]

Empirical studies have found a drastic decline of road transportation as regards occupation rate, bus frequency, revenue and passenger volume for bus connections overlapping with newly built HSR lines. Amongst others, this modal shift can be witnessed on the HSR lines of Ningbo-Hangzhou, Beijing-Tianjin, Hefei-Fuzhou, Changsha-Loudi, and Shenzhen-Guangzhou as shown in **Table 1**. The Ningbo-Hangzhou HSR has cut its revenue and occupation rate of competing bus routes by 68 % and 25.89 %. The number of buses between Beijing and Tianjin decreased by 48.2 % one year after the opening of HSR.[33]

[28] Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. China's High-Speed Rail Development. International Development in Focus. Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

[29] Wang Shaobo, Guo Jianke, Luo Xiaolong, et al. *The spatial impact of HSR on air travels in major cities: a perspective of time value per capita. Progress in Geography,* 2019(11): 1-10. [61].

[30] Sun Feng, Wang Degen, Niu Yu. *Analysis of HSR competition with automobile and aviation. Geographical Research,* 2017, 36(1): 171-187.

[31] Wang Jiao'e, Jing Yue, Yang Haoran. *Measurement of substitution effect of HSR on domestic civil aviation. Journal of Natural Resources,* 2019, 34(9): 1933-1944.

[32] Wang Shaobo, Guo Jianke, Luo Xiaolong, et al. *The spatial impact of HSR on air travels in major cities: a perspective of time value per capita. Progress in Geography,* 2019(11): 1-10.

[33] Sun Feng, Wang Degen, Niu Yu. *Analysis of HSR competition with automobile and aviation. Geographical Research,* 2017, 36(1): 171-187.

Table 1 Media Coverage of HSR Impacts on Road Passenger Transport[34]

Train	Mileage (km)	Impact
Ningbo-Hangzhou	236	After its opening in July 2013, the monthly occupation rate of the bus line dropped from 54.39 % to 28.51 % year-on-year. The daily ridership dropped from 500 to 150, and the revenue from 50,000 to 16,000 CNY.
Beijing-Tianjin	112	After its opening in August 2008, the competing bus line reduced daily frequencies from 83 to 43 and monthly ridership from 47,400 to 36,700.
Hefei-Fuzhou	675	After its opening in June 2015, the competing bus lines were either canceled or less frequent due to lacking passengers. The ridership of Fuzhou-Nanping bus route declined by 40 %.
Changsha-Loudi	114	After operations of the Hunan segment of the Shanghai-Kunming HSR railway in December 2014, buses from Changsha West and South to Huaihua, Fenghuang, Loudi and Shaoyang directions had over 50 % and 80 % of ridership decline.
Shenzhen-Guangzhou	105	After the segment of Wuhan-Guangzhou opened in December 2011, buses from Guangzhou to Dongguan and Shenzhen directions had 19.13 % and 30.32 % less passengers during the following Spring Festival period.

Despite limited research on the impacts of HSR on its substitution of road transport due to difficulty in obtaining data, there is a growing literature available based on analyses through questionnaire surveys and logit selection models (linked the probability of consumer choices), which indicate that HSR lines have encouraged some passengers to shift from road to rail travel. For example, the shares of highway and HSR transportation between the Chinese cities Changchun and Jilin (about 90 km apart) account for about 30 % and 70 %, while for the connection between Shenzhen and Shanwei (distance of 200 km), it accounts for 50 % each.[35,36]

A recent study evaluated the HSR substitution effect on airplanes and cars after the completion of the eight vertical and eight horizontal corridors to be 12 % of the civil aviation market share and 32 % of the road travel market, respectively.[37]

Research found that the faster the HSR and the shorter the distance between cities, the more pronounced the substitution effect on competing civil aviation routes is.[38] Another site survey was conducted to quantify the changes of ridership among transportation modes, which concluded that greater impacts are felt by civil aviation in medium and small-sized cities compared with large cities, and more in central than Eastern and Western regions[39]. Further studies also show that the passenger traffic of low-cost airlines has declined as a consequence of HSR development.[40,41] Further substitution analysis of HSR to civil aviation can be found in chapter 2. Aside from substitution effects, HSR construction has also led to inducement effects, referring to the stimulation of other transportation modes around HSR stations.

34 Sun Feng, Wang Degen, Niu Yu. *Analysis of HSR competition with automobile and aviation. Geographical Research,* 2017, 36(1): 171-187.
35 Sha Junlin. *Research on the sharing rate and development strategy of road passenger transport under the influence of HSR*. Changchun: Jilin University, 2012.
36 Luo Yunhui. *HSR Impact on highway passenger transport in small and medium-sized cities and its countermeasures.* Guangzhou: South China University of Technology, 2015.
37 Weng Jin, Xiao Jiaying, Li Xin. *HSR Demand Substitution Assessment: A study based on global network. Xinjiang Finance and Economics*. 2021, (2), 5-16.
38 Wang Jiao'e, Jing Yue, Yang Haoran. *Measurement of substitution effect of HSR on domestic civil aviation. Journal of Natural Resources,* 2019, 34(9): 1933-1944.
39 Wang Jiao'e, Jiao Jingjuan, Jin Fengjun. *HSR influence on the spatial interactions of Chinese cities. Acta Geographica Sinica,* 2014, 69(12): 1833-1846.
40 Su M, Luan W, Fu X, et al. *The competition effects of low-cost carriers and high-speed rail on the Chinese aviation market.* Transport Policy, 2020, 95: 37-46.
41 Clewlow R R, Sussman J M, Balakrishnan H. *The impact of high-speed rail and low-cost carriers on European air passenger traffic.* Transport Policy, 2014, 33: 136-143.

1.4.4 Fares

Although HSR fares in China equal only 25 % of the European price level, they nonetheless amount to 300-400 % of ordinary domestic trains.[42] China's HSR pricing considers both the competition with other transportation modes and the affordability for the public. From 2007 to 2016, HSR fares remained largely on the same price level. The surge of HSR ridership over the course of this period indicates a strong willingness among Chinese consumers to choose HSR for reasons of convenience and comfort. In 2017, the fares of certain HSR lines were raised by 10-50 %.[43] Research shows that HSR mainly appeals to business and leisure travelers; those choosing HSR have an income level 30-50 % higher than that of regular train passengers. However, the general preference of HSR over regular trains is present in all income groups.[44]

[42] Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. *China's High-Speed Rail Development. International Development in Focus*. Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

[43] Lu Yanan. *With adjusted HSR fares, which train do you take?* [2017-04-12]. http://finance.people.com.cn/BIG5/n1/2017/0412/c1004-29203849.html.

[44] Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. *China's High-Speed Rail Development. International Development in Focus*. Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

1.4.5 Impact Analysis

Economy. HSR influences the economy both directly and indirectly on a broader level, which starts with higher demand for business and leisure travel, ease of traveling, and economic opportunities of large and medium-sized cities. Research found that HSR has a positive sway on economic integration,[45] regional growth and population.[46,47, 48]

In the meantime, in the frame of large-scale government investment projects, HSR construction contributes to GDP growth and economic stability, fueling related sectors such as steel, concrete, cement and other building materials. Statistics show that the average usage of steel bars, concrete and cement during the construction phase of the Beijing-Shanghai HSR was 10,000 tons, 110,000 cubic metres and 35,000 tons in a day.

Society. HSR boosts the employment market and income levels. The number of job opportunities continues to increase from the R&D to construction phase. HSR also contributes to poverty alleviation by its inclusion of underdeveloped or poverty-stricken areas. Those are exemplified by the HSR lines between Baoji-Lanzhou, Xining-Chengdu and Chongqing-Guizhou, which have effectively improved the coordination between rural and regional vitalisation as well as targeted poverty reduction.

In addition, HSR has amplified urbanisation and tourism. New HSR lines often pass new urban areas being built in small and medium-sized cities, and HSR stations, which are often located in undeveloped areas, giving rise to so-called"HSR New Towns".

Ecology and other sustainability aspects. Irrespective of its economic prospects, the ecological impacts of HSR should also be addressed in light of sustainability criteria.

The entire lifecycle of HSR projects, from planning to material provision, construction, operation, maintenance and decommissioning, causes emissions.[49] Meanwhile, HSR development has overall showed strong advantages in terms of energy conservation and overall emission reduction of the transport sector.

Compared with road travel and civil aviation,[50,51] the ratio of energy consumption between the three modes equals 1:5:6.[52] Furthermore, studies have shown that the introduction of HSR has reduced urban CO_2 emission significantly, and additional 100 HSR trips can reduce CO_2 emission by 0.14 %.[53] More information on the carbon emission analysis of HSR can be found in chapter 3.

[45] Chen Z, Haynes K E. *Impact of high-speed rail on housing values: an observation from the Beijing-Shanghai line.* Journal of Transport Geography, 2015, 43: 91-100.

[46] Ke X, Chen H, Hong Y, et al. *Do China's high-speed-rail projects promote local economy? - New evidence from a panel data approach.* China Economic Review, 2017, 44: 203-226.

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[48] Gao Y, Song S, Sun J, et al. Does high-speed rail connection really promote local economy? Evidence from China's Yangtze River Delta. Review of Development Economics, 2020, 24(1): 316-338.

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[50] Zhou Xinjun. *Analysis of Decarbonizstion and Environmental Effects of HSR Operations. Power and Energy,* 2013, 34(03): 212-216.

[51] Wang Y, Zhou S, Ou X. *Development and application of a life cycle energy consumption and CO_2 emission analysis model for high-speed railway transport in China. Advances in Climate Change Research,* 2021, 12(2): 270-280.

[52] Cui Lixin. *A Comparative Research of HSR and Other Transportation Modes on Energy Conservation and Emission Reduction.* Beijing: Beijing Jiaotong University, 2010.

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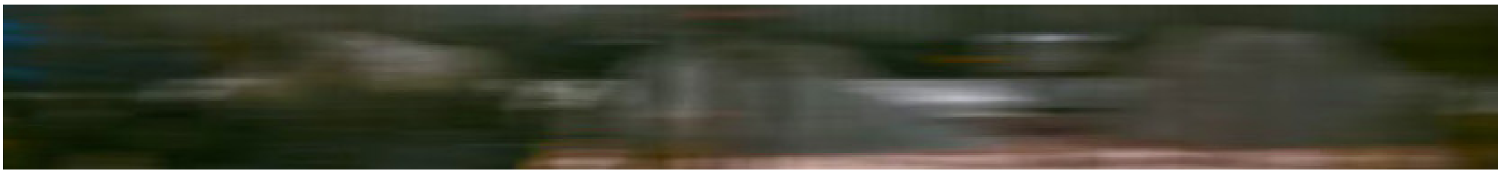
◆ Chapter II ◆

HSR-Aviation Substitution and Emission Reduction Analysis



This chapter focuses on the quantitative analysis of the substitution effect of HSR to civil aviation using the difference-in-difference (DID) methodology, beginning with an impact analysis of different distances, frequencies and locations based on traffic statistics from 2008 to 2017, which correspond to the timeframe of the four vertical and four horizontal corridors in order to reflect the evolution of HSR in China. Later, based on the planning of the eight vertical and eight horizontal corridors as well as the HSR accessibility goal for cities with a population over 500,000 inhabitants, the volume of civil aviation to be substituted by HSR upon the completed construction will be estimated.

2.1 Literature Review

The HSR network in China has already formed a network covering developed cities, which typically demand large capacity of flight connections. In this context, strong competition exists between HSR and civil aviation on the passenger transportation market.[54] Newly built HSR lines have a particular impact on short-haul flights, which has already led to the shutdown of a number of flight connections.[55] Notably, flights on the routes between Zhengzhou-Xi'an, Nanjing-Wuhan, and Chengdu-Chongqing went from 3 times a day to cancelation six months after the opening of competing HSR lines.[56] Data analyses from the period 1994–2012 have shown that the substituting effect of HSR introduction is strongest for the distance range of 500–800 km.[57] Flights within 900 km are still affected by modal shifts as well. For instance, the monthly passenger volume on flights between Guangzhou-Wuhan dropped from 120,000 to 60,000 after the launch of a new HSR line. It is anticipated that continuous HSR expansion will lead to further shutdown of flight routes.

Many studies focus on a specific HSR route or area for the simulation analysis of consumer choices between HSR and aviation. Research on long-distance departures from Chongqing found that passengers with lower income favour regular trains, such preference being most prevalent in central and Western regions.[58] A study on the impacts of HSR of flight traffic and ticket fares concludes that despite regional variations, HSR has cut the passenger traffic of competing flights by over 50 %.[59] Another study analysed the strategies taken by three large air carriers under the pressure of HSR from 2010 and 2013, which found that the introduction of HSR has a significant impact on air traffic, and that the competitiveness of HSR is comparatively sensitive to price levels. [60]

In sum, distance and duration are the defining factors of the HSR's competitiveness, which declines as either factor increases. A research based on panel dataset from 2007 to 2014 analysed the impact on flight frequency and occupancy found that HSR is superior in travels within 2 hours and remains competitive within 5 hours or 1,350 km (equal to, for example, the distance between Berlin and Paris of 1088 km) .[61] Another research categorised HSR competitiveness into three ranges: under 500 km, 500-800 km and above 800 km, which concluded that HSR is most impactful in 500-800 km trips where the flights lose 34 % of passenger traffic on average.[62] Concurrently, statistics of the Beijing-Chongqing HSR line (distance around 1,800 km) from 2011 to 2014 show that the market share of HSR was only 0.9 %, pointing to the secondary role of HSR in long-haul travel.[63]

[54] Ding Jinxue, Jin Fengjun, Wang Jiao'e, et al. *The competition between HSR and civil aviation and its spatial effects: Beijing- Shanghai HSR line. Economic Geography,* 2013, 33(05): 104-110.

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[57] Wan Y, Ha H, Yoshida Y, et al. Airlines' reaction to high-speed rail entries: Empirical study of the Northeast Asian market. Transportation Research Part A: Policy and Practice, 2016, 94: 532-557.

[58] Ren X, Chen Z, Wang F, et al. Impact of high-speed rail on social equity in China: Evidence from a mode choice survey. Transportation Research Part A: Policy and Practice, 2020, 138: 422-441.

[59] Li H, Strauss J, Lu L. The impact of high-speed rail on civil aviation in China. Transport Policy, 2019, 74: 187-200.

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

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[63] Li Z, Sheng D. Forecasting passenger travel demand for air and high-speed rail integration service: A case study of Beijing-Guangzhou corridor, China. Transportation Research Part A: Policy and Practice, 2016, 94: 397-410.

2.2 Methodology

2.2.1 Difference-in-Difference Methodology

The difference-in-difference (DID) is a methodology to analyse and evaluate policy effects, and a common approach to causality estimation and outcome assessment of policies. Based on two dimensions of time and policy affectedness, sampled individuals are divided into four cohorts: a treatment group, which is affected by the policy, and a control group, which remains unaffected, with their respective data being analysed both before and after the policy implementation. The DID is built on the hypothesis of a common parallel trend, so that in the absence of the policy, the two post-policy groups would exhibit the same trend of change, meaning that the effect of unobservable factors on the two groups are consistent.

Based on the decision-making process of state authorities, the four vertical and four horizontal corridors depict a policy, which is not the result of the aviation industry. Furthermore, the policy creates externalities that impact air transportation, where DID modelling could be leveraged to understand the consequences on flight frequency and passenger traffic. For the purpose of analysis, the treatment group consists of cities with HSR access between 2008 and 2017 and the control group comprises cities without direct HSR access. The study examines the service schedule and passenger volume statistics of flight routes. For flight connections in the treatment group, both HSR services and civil aviation is available.

2.2.2 Variable Selection

This study uses GDP (10,000 CNY), residents (10,000 persons) and internet users (10,000 persons) as control variables to reflect the development level of city pairs connected by airlines. Sums of the two cities in a pair are used in the calculation.

The annual service schedule and passenger volumes of flight routes are dependent variable indicators that reflect the changes in the activity level of passenger aviation. Service schedule indicates the activity level of the route, and passenger traffic represents passengers carried on scheduled services.

The independent HSR variables include duration, distance and frequency. The operating speed of HSR is divided into 350 km/h and 250 km/h, and duration differs across city pairs due to variation in speed and the number of stops. Duration and frequency have a direct correlation to the competitiveness of HSR, which is assessed against flights with the same time schedule. Distance, notably the track length between the paired cities, is used to analyse the HSR's distance-related competitiveness against air travel. Frequency is the number of HSR trips between paired cities, which indicates the convenience of HSR traveling. See **Table 2** for the selected variables.

Table 2 Variables of the HSR-Aviation Substitution Model

Variable	Parameter	Variable Description
Dependent variable	Flights scheduled	Annual number of scheduled flights
	Passenger traffic	Annual number of passenger traffic (unit: person)
Control variable	Total GDP	Sum of GDP of city pair (unit: 10,000 yuan)
	Total internet users	Sum of internet users of city pair (unit: 10,000 person)
	Total population	Sum of residents of city pair (unit: 10,000 person)
Independent HSR variable	Frequency	HSR intervals between paired cities (unit: time/day)
	Duration	Travel time between paired cities (unit: hour)
	Distance	Distance between paired cities (unit: km)

2.3 Main Data

2.3.1 Sampled Data

The study constructs a panel data set based on sampled data of flight routes between 2008 and 2017, covering the period from China's first HSR line to the completion of the four vertical and four horizontal corridors. With flight data from *Statistical Data on Civil Aviation of China*[64] and Variflight.com[65], statistics of the 362 paired cities on the 32 key nodes of the four vertical and four horizontal corridors from 2007 to 2018 were analysed.

The 32 key cities (treatment group) include: Beijing, Shijiazhuang, Zhengzhou, Wuhan, Changsha, Guangzhou, Shenzhen, Harbin, Dalian, Tianjin, Jinan, Xuzhou, Nanjing, Shanghai, Ningbo, Fuzhou, Xiamen, Taiyuan, Qingdao, Shenyang, Lanzhou, Xi'an, Chengdu, Chongqing, Hefei, Kunming, Guiyang, Nanchang, Hangzhou, Wenzhou, Wuxi and Changzhou. Other cities (control group) are mainly selected for the larger passenger volume and annual number of flights.

The control group includes active routes with 22 cities, comprising: Haikou, Sanya, Urumqi, Ordos, Yinchuan, Hohhot, Lhasa, Xining, Kashgar, Mangshi (Yunnan), Yinchuan, Baotou, Zhuhai, Guilin, Yining, Jiuzhaigou (Aba Prefecture), Altay, Diqing, Dali, Shantou, Korla and Aksu, which are more developed in terms of economy or tourism. The sampled 362 flight routes include 285 routes in the treatment group and 77 routes in the control group. The control groups did not have HSR access in 2017.

2.3.2 Variable Data

The panel data reflects the changes of activity level of the 362 flight routes between 2008 and 2017. For the 285 city pairs in the treatment group, 1 city pair had HSR access in 2008, 5 in 2009, 12 in 2010, 12 in 2011, 31 in 2012, 59 in 2013, 49 in 2014, 70 in 2015, 40 in 2016 and 6 in 2017. The cities which have not been connected to the HSR grid by 2017 are characterised by comparatively lower socio-economic levels, in turn leading to overall lower activity level of flights in the control group. See **Table 3** for details of sampled data. Paired cities distanced between 1,000 km and 1,500 km have more flights and those with 0-600 km have less. **Table 4** shows the statistical results of other variables.

[64] Department of Development Planning, Civil Aviation Administration of China. *Statistical Data on Civil Aviation of China 2018*. Beijing: Civil Aviation Press of China, 2019.

[65] Variflight.com data. Variflight.com big data platform. [2019-10-2]. https://data.variflight.com/.

Table 3 Scheduled Service and Passenger Traffic

City Pair Distance (km)	Observables	Passenger Traffic (10,000 persons)		Scheduled Flights	
	(city pair*year)	average value	standard deviation	average value	standard deviation
All samples	3,620	58.20	72.65	5,598.37	4,215.05
0~600	280	29.78	26.12	4,313.03	1,770.55
600~1000	590	46.00	42.65	5,118.37	2,687.37
1000~1500	750	65.89	92.41	6,037.91	5,124.4
1500~2000	880	62.53	73.44	5,731.18	4,666.33
>2000	1,120	63.17	75.02	5,773.89	4,181.70
Control Group	770	48.01	38.69	4,161.59	2,696.99
Treatment Group	2,850	60.95	79.15	5,986.55	4,460.54

Table 4 City Pairs and HSR Variables

	Unit	Average Value	Standard Deviation
Total population	10,000 persons	1,596.18	829.56
Total GDP	100 million yuan	15,092.50	8,751.07
Total internet users	10,000 persons	345.59	409.02
Frequency	Time	4.02	11.11
Duration	Hour	6.87	9.16

2.4 Data Analysis

Using the DID methodology described in 2.2, a statistical analysis with data from 2.3 can be obtained.

The study assesses the impacts of introduction and frequency of HSR, as shown in formulas (2-1) and (2-4).

See formulas (2-1) and (2-2) for the impact assessment of HSR introduction:

$$\ln(FreqAvi_{i,t}) = \alpha_0 + \alpha_1 \ln(TGDP_{i,t}) + \alpha_2 \ln(TPop_{i,t}) + \alpha_3 \ln(TInt_{i,t}) + \alpha_4 HSRIntro_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}1)$$

$$\ln(QuantityTrans_{i,t}) = \beta_0 + \beta_1 \ln(TGDP_{i,t}) + \beta_2 \ln(TPop_{i,t}) + \beta_3 \ln(TInt_{i,t}) + \beta_4 HSRIntro_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}2)$$

FreqAvi = number of transport flights of the route
TGDP = sum of the GDP of the city pair
TPop = sum of the population of the city pair
TInt = the total number of city pairs connected to the Internet
HSRIntro = HSR connection has been introduced
Dyear = control for fixed effect of time
DRoute = control for fixed effect of route
i = each city pair and route
t = sample for each period included
a_4 = average substitution effect of HSR on number of civil aviation transport flights

The regression model for the number of passengers is similar to that of transport frequency:
QuantityTrans = number of passengers per year on the route
β_4 = average substitution effect of high-speed rail on the number of transporters on the route.
The coefficients of most interest in this study are α_4 and β_4.

The impact of HSR frequency on the substitution effect is evaluated separately as shown in equations (2-3) and (2-4):

$$\ln(FreqAvi_{i,t}) = \alpha_0 + \alpha_1 \ln(TGDP_{i,t}) + \alpha_2 \ln(TPop_{i,t}) + \alpha_3 \ln(TInt_{i,t}) + \alpha_4 HSRFreq_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}3)$$

$$\ln(QuantityTrans_{i,t}) = \beta_0 + \beta_1 \ln(TGDP_{i,t}) + \beta_2 \ln(TPop_{i,t}) + \beta_3 \ln(TInt_{i,t}) + \beta_4 HSRFreq_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}4)$$

HSRFreq = number of direct high speed trains running between city pairs per day.

The study introduces interaction terms to study the heterogeneity of inland and coastal routes of different distance and duration in order to analyse the relative competitiveness of HSR across cities, as shown in formulas (2-5) and (2-6).

$$\ln(FreqAvi_{i,t}) = \alpha_0 + \alpha_1 \ln(TGDP_{i,t}) + \alpha_2 \ln(TPop_{i,t}) + \alpha_3 \ln(TInt_{i,t}) + \alpha_4 HSRIntro_{i,t} + \alpha_6 HSRIntro_{i,t} \cdot Dum_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}5)$$

$$\ln(QuantityTrans_{i,t}) = \alpha_0 + \alpha_1 \ln(TGDP_{i,t}) + \alpha_2 \ln(TPop_{i,t}) + \alpha_3 \ln(TInt_{i,t}) + \alpha_4 HSRIntro_{i,t} + \alpha_6 HSRIntro_{i,t} \cdot Dum_{i,t} + Dyear_t + DRoute_i + \varepsilon_{i,t} \quad (2\text{-}6)$$

Distance and Time denote the running distance and running time of city-to-city HSR respectively

Dum (Distance>1,400) = 1 (when running distance of city-to-city HSR is more than 1,400 km) and 0 (when it is less than 1,400 km).

Dum (Time>4) = 1 (when running time of city-to-city HSR is more than 4 hours) and 0 (when it is less than 4 hours)

a_4 and a_6 are the most relevant coefficients in the study, representing additional effects of HSR-aviation substitution under specific circumstances.

2.4.1 Outcomes

The average impacts on the number of flights and passengers in cities connected by the four vertical and four horizontal corridors are 28.7 % and 31.8 %, respectively. The increase of HSR frequency significantly reduces air passenger traffic. The introduction of HSR exhibits an apparent lagged effect, leading to major impacts becoming evident only two to three years after the HSR launch, whereas impacts during the first year are limited. The influence of HSR increases with time, and the quantity of flights and passengers decline around 40 % in cities with HSR access. The substitution of HSR to air travel in the first year is around 30 %.

2.4.2 Impact of Duration on Competitiveness

Long duration of HSR travel affects passenger comfort and time value, thus hampering its appeals to consumers. While consumers' preference of HSR remains when travel time exceeds 4 and 6 hours, its impact on the activity level of airplanes declines, where 17.6 % and 13.5 % flight routes are replaced by HSR trips over 4 and 6 hours, and passenger traffic are cut by 14.8 % and 11.8 %. The impact on the modal shift is the most evident for HSR travels of a duration of 2-4 hours, replacing 75.3 % of overlapping passenger flights, with further replacement rates of 42.3 %, 12.8 %, 10.8 % and 5.5 % for the duration of 4-6, 6-8, 8-10 hours and over 10 hours of HSR travel duration, respectively. Aligning with results from previous studies, it could be seen that HSR trips exceeding 10 hours have the least impact on air service. In general, the most impactful duration is less than 6 hours (or 1,500 km) and the fiercest competition in the range of 500-1,500 km, comparable to routes such as Berlin to Paris (approx. 1,100 km) or Munich (approx. 600 km). The analysis of passenger traffic and service scheduled show similar results. For the five segments of duration above, the substitution rates of HSR to air are 83.5 %, 62.4 %, 15.2 %, 13.1 % and 11.1 %, respectively.

2.4.3 Impact of Distance on Competitiveness

As the distance of a HSR trip increases, its share in intercity passenger transportation decreases. Longer distance means less attraction of HSR travel, a sign of its secondary role in long-haul journeys. The distance of HSR is divided into 4 ranges: 0-600 km, 600-1,000 km, 1,000-1,500 km and above 1,500 km, which impact service scheduled by 71.8 %, 56.4 %, 24.5 % and 9.9 % correspondingly. The competitiveness of HSR abates sharply when the distance is over 1,000 km. The study shows that HSR in China is highly competitive when the distance is within 1,000 km, where a clear HSR-air substitution effect is observed, which becomes feeble when exceeding 1,400 km.

2.4.4 Impact of Location on Competitiveness

Research shows that the impact level on flights from West to East is lower than national average, which may relate to the lacking competitiveness on long-haul transportation as well as the older and slower tracks along the Yangtze River. Meanwhile, flights from central to Western China are also less affected, with the substitution effects being 25.2 % and 42.1 % for service scheduled and passenger traffic. On the one hand, the HSR network concentrates on Eastern China and the HSR density in central and Western regions remains low. On the other hand, as shown previously, the potential of HSR-air substitution is limited in long-haul travel.

2.5 Impact Outlook of HSR on Civil Aviation

2.5.1 Impacts of HSR eight vertical and eight horizontal corridors

As China implements its HSR scale-up policies, more airports and regions will be covered by the HSR network. As the four vertical and four horizontal corridors upgrade to eight corridors respectively, an additional 69 airports will be included in the network, which is currently consisting of 71 airports, most of which are located in central and Eastern China. The impacts of HSR on passenger aviation will be twofold:
1) less passenger traffic in competing flights;
2) reduced flight offer on flight connections covered by HSR lines after speeding-up and shortening of existing railway lines. **Table 5** shows the passenger traffic between the airports currently covered and those to be covered by the expanding HSR network.

Airports under the eight vertical and eight horizontal corridors involve 834 existing flight routes whose duration is mostly under 8 hours. According to statistics from 2018, the number of scheduled flights declined by 174,000, 128,000, 45,000 and 13,000 for the duration of 0-4, 4-6, 6-8 and 8-10 hours, respectively, which means 366,000 flights were replaced by HSR and the overall HSR-aviation substitution rate was 8.8 %. In terms of geographical distribution, 72.3 % flights were connections in Eastern China.

Some HSR lines will speed up under the planning of the eight vertical and eight horizontal corridors, benefiting 64 lines along the river and coast, among which 5 HSR lines will be shortened to travel durations within 4 hours. Under the same assumed substitution rate, 24,000 flights could be replaced and the overall substitution rate of all flights could increase by another 0.7 % compared to 2018 data.

Table 5 Impact Analysis of Eight Vertical and Eight Horizontal Corridors (2018 Flight Statistics)

Duration	Substitution(%)	Flight Routes	Number of Flights	Flights Substituted
0~4 hours	75	205	232,579	174,434
4~6 hours	42	243	303,884	127,631
6~8 hours	13	225	349,898	45,487
8~10 hours	11	101	119,302	13,123
>10 hours	6	59	85,373	5,122

2.5.2 HSR impact on cities with a population over 500,000 inhabitants

Once all cities with a population over 500,000 inhabitants are connected to HSR, almost all airports in China will be covered by the HSR network. On the basis of statistics from 2018, HSR trips with duration of 0-4, 4-6, 6-8 and 8-10 hours could replace 513,000, 331,000, 112,000 and 76,000 flights or a total of 1.087 million flights, respectively, equaling to an overall substitution rate of 26.2 %.

Table 6 Impact Analysis: HSR Accessibility of Cities with a Population over 500,000 (2018)

Duration	Substitution (%)	Flights Scheduled	Flights Replaced
0-4 hours	75	683,393	512,545
4-6 hours	42	787,143	330,600
6-8 hours	13	864,389	112,371
8-10 hours	11	686,863	75,555
>10 hours	6	938,623	56,317

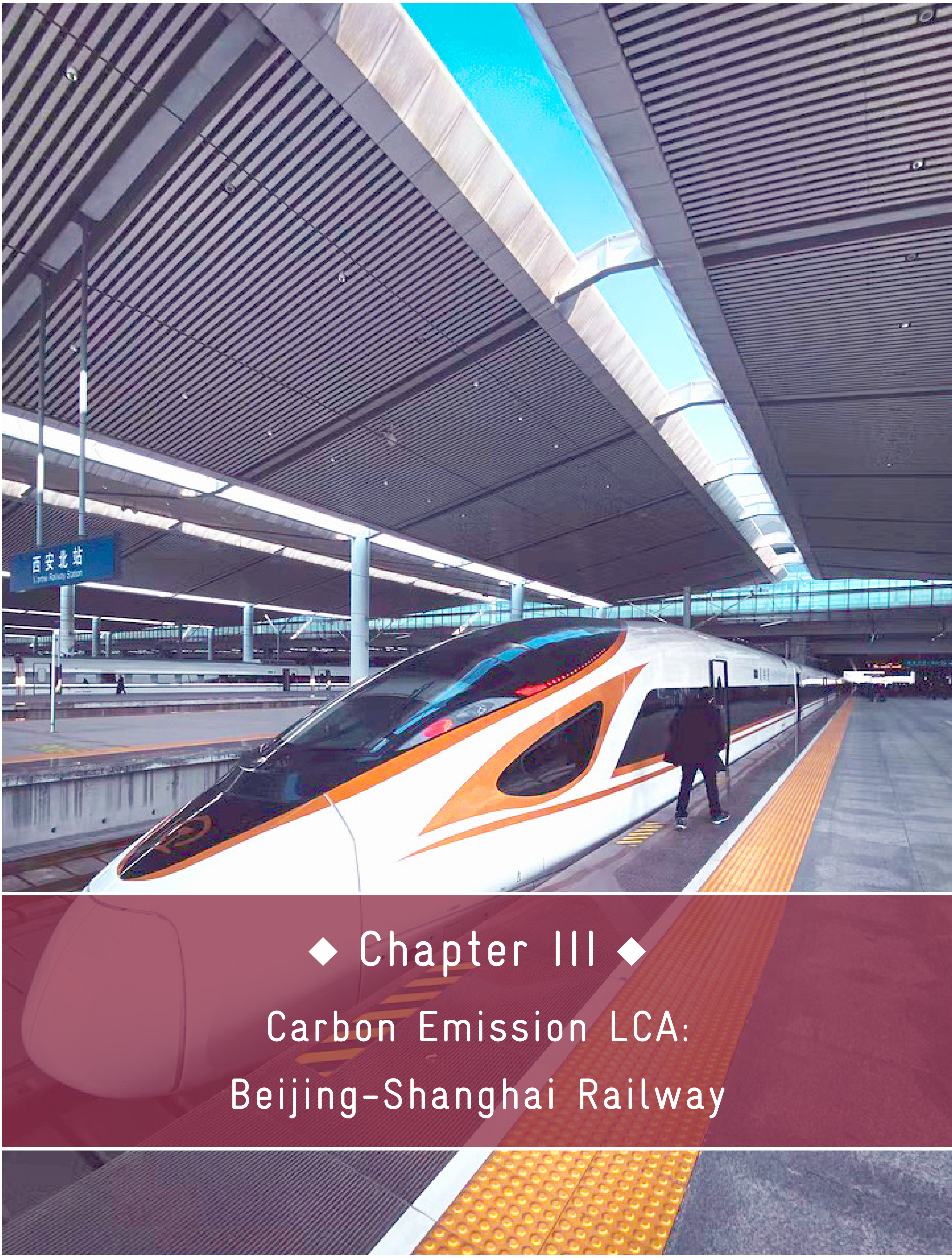
2.6 HSR/Aviation Substitution: Estimation of Emission Reduction

The future modal shift from air travel to HSR will contribute to emission reduction of the civil aviation sector. An estimation is conducted based on the 2018 statistics including parameters of flight routes, energy consumption of different aircraft types during take-off, cruising distance, energy efficiency etc. in order to calculate the decarbonising benefits of HSR planning. Most flight routes affected by the eight vertical and eight horizontal corridors are operated by narrow-body aircrafts and regional aircrafts, with the former taking up 88.2 %. After data correction of the energy efficiency considering the fuel performance and cruising distance of aircraft types, the benefits of emission reduction brought by HSR is shown in **Table 7**.

For flights in 2018, the energy conservation amounted to 42,000, 201,000, 134,000, 172,000 and 72,000 tons of jet fuel for air travel lasting 0-4, 4-6, 6-8, 8-10 and over 10 hours, respectively, totaling 1.878 million tons of direct annual emission reduction. As the demand for aviation will rise, the results in the study are more conservative than the actual emissions saved by the eight vertical and eight horizontal corridors. Similarly, with HSR accessibility for cities with a population over 500,000 inhabitants, energy conserved by HSR per year will amount to 2.089 million tons of jet fuel and 6.311 million tons of direct carbon emissions.

Table 7 Emission Reduction on Flight Routes Affected by the Eight Vertical and Eight Horizontal Corridors

Duration	Substitution	Energy Conservation and Kerosene Reduction	CO_2 Emission Reduction
	(%)	(10,000 tons)	(10,000 tons)
0-4 hours	75	4.2	12.8
4-6 hours	42	20.1	60.7
6-8 hours	13	13.4	40.6
8-10 hours	11	17.2	52.0
>10 hours	6	7.2	21.7



◆ Chapter III ◆

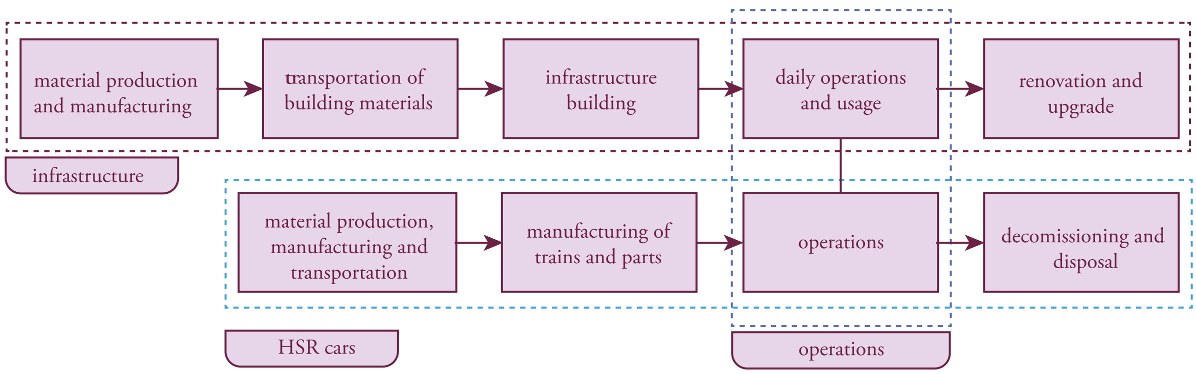
Carbon Emission LCA: Beijing-Shanghai Railway

3.1 Case Profile

Lifecycle-based analysis (LCA) is an objective methodology to evaluate the energy performance of HSR, which consumes energy and produces GHG throughout its lifecycle from construction to operations. This chapter provides a case study with LCA methodology to quantify the CO_2 emission of the Beijing-Shanghai railway.[68]

The calculation in this paper includes three cycles, notably the infrastructure cycle, vehicle cycle and operation cycle (see **Figure 4**). The infrastructure cycle consists of six sub-construction cycles, containing road bed-, bridge-, tunnel- and track construction, set-up of electrification systems and building of HSR train stations. The HSR vehicle cycle entails three main phases, namely construction, maintenance and disposal. Energy consumption and CO_2 emissions are mainly caused by the operation cycle, due to high electricity consumption for the daily operation of HSR trains and train stations, respectively. High passenger traffic can here be taken as a benchmark to assess the HSR activity levels amidst its entire lifecycle.

Figure 4 HSR Lifecycle: Cycle Division



From public information, the specific volume of six sub-projects of the Beijing-Shanghai HSR line can be obtained. The line has a total length of 1,318 km and a designed speed limit of 380 km/h, there are 24 stations along the Beijing-Shanghai line, transporting 200 million passengers per year.[69, 70]

The lengths of roadbed, bridges and culverts, tunnels, ballast-less and ballasted tracks are 464 km, 1,160 km, 16 km, 1,200 km and 366 km, respectively. Electrification is available through the entire track-length of the railway.[71, 72]

[68] Reference for more details: Wang Y, Zhou S, Ou X. *Development and application of a life cycle energy consumption and CO_2 emission analysis model for high-speed railway transport in China.* Advances in Climate Change Research, 2021, 12(2): 270-280.

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3.2 Main Data and Hypothesis

A hypothesis can be proposed for the operations of the Beijing-Shanghai HSR line using key data and assumptions shown in **Table 8**. It is assumed that only the CRH380B trainset is used, which is configured with 16 carriages (8M+8T), 980 tons of weight, a seating capacity of 1,060 (staff included), and estimated weight per capita of 100 kg (luggage included). Maintenance is required in the average service life of 20 years. The target operating speed is 300 km/h with an average train occupancy rate (TOR) of 80 %. The average distance covered per HSR trip is 900 km, transporting 200 million riders each year and running a return trip daily (1,800 km in total). Suppose that energy consumption and carbon emissions are deriving from electricity usage, the power consumption of HSR operations is correlated to ridership onboard, whereby its electricity usage is estimated to be 6 % of the total power usage of HSR operations.[73,74,75]

Table 8 Main Parameters

Parameter	Average Traveling Distance (km)	Target Speed (km/h)	Average TOR (%)	Total Weight (train + people) (tons)	Annual Passenger Flow (million)
	900	300	80	1,064.8	200

Parameter	Average Distance Between Two Successive Stations (km)	Service Life (years)	Electricity Usage of Stations/Trains in Operation (%)
	57.3	20	6

The HSR unit consumption means the average power consumption per unit mass of HSR trains traveling per unit distance (kWh/t km). Calculations based on the parameters in **Table 8** show that the unit consumption of passenger turnover corrected for the Beijing-Shanghai HSR is 445.7 kWh/10,000 pkm, which will be used in the subsequent evaluation of the energy consumption and carbon intensity of HSR transportation.

Based on the lists of building materials and energy resources during the construction phase, and information including the one-time mandatory replacement of tracks and four-time replacement of electrification system in the calculated service life of 100 years during the operational phase, the energy consumption and carbon emissions of the infrastructure cycle can be calculated as shown in **Table 9**.

Similarly, energy consumption and carbon emissions of a HSR train during its rolling stock cycle can be calculated, as shown in **Table 10**.

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Table 9 Infrastructure Cycle: Energy Consumption and Carbon Emissions

Phase	Energy Consumption (MJ)	Share (%)	Carbon Emissions ($kgCO_{2e}$)	Share (%)
Material Manufacturing	2.082×10^{11}	63.20	3.158×10^{10}	75.43
Logistics and Construction	5.215×10^{10}	15.83	4.464×10^{9}	10.66
Renovation and Upgrade	6.906×10^{10}	20.97	5.824×10^{9}	13.91
Total	3.294×10^{11}	100	4.187×10^{10}	100

Table 10 Rolling Stock Cycle: Energy Consumption and Carbon Emissions

Phase	Energy Consumption (MJ)	Share (%)	Carbon Emissions ($kgCO_{2e}$)	Share (%)
Manufacturing	9.685×10^{7}	42.55	8.620×10^{6}	48.16
Maintenance	1.307×10^{8}	57.45	9.279×10^{6}	51.84
Decommissioning and Disposal	8.854	0.00	5.536	0.00
Total	2.276×10^{8}	100	1.790×10^{7}	100

3.3 Results

Based on Figure 4 in 3.1 and statistics in 3.2 using the below analysis model, the following results are obtained.

Using the quantities of final energy and materials used and transported, energy consumption and the dual factors of carbon emissions in the calculation, the formulae to calculate total energy consumption Q and carbon emissions C throughout the HSR lifecycle, as well as energy consumption q and carbon emissions c based on unit service (pkm) are shown in (3-1) - (3-4):

$$Q = \sum_{j=1}^{3}\sum_{k}\sum_{i} m_{ijk} \cdot \rho_i(t) \qquad (3\text{-}1)$$

$$C = \sum_{j=1}^{3}\sum_{k}\sum_{i} m_{ijk} \cdot \sigma_i(t) \qquad (3\text{-}2)$$

$$q = \frac{Q}{S} \qquad (3\text{-}3)$$

$$c = \frac{C}{S} \qquad (3\text{-}4)$$

m_{ijk} = final energy, materials or transportation mode used (loss included) in phase k of cycle j

$\rho i(t)$ = primary fossil fuel consumption factor of at time t

$\sigma i(t)$ = GHG emissions factor of at time t

S = the total service quantity of transport services (unit: pkm) throughout the HSR lifecycle

Energy consumption and emission of HSR operations are approximated using formulae (3-5) and (3-6), since the lifecycle-based power usage is unavailable.

$$Q_{yx} = \sum_{t}\sum_{i} q_i(t) \cdot N_i(t) \cdot L \cdot \chi_e \qquad (3\text{-}5)$$

$$C_{yx} = \sum_{t}\sum_{i} q_i(t) \cdot N_i(t) \cdot L \cdot \delta_e \qquad (3\text{-}6)$$

$qi(t)$ = unit service consumption (kwh/10,000 pkm) of train i at time t.

L = average travelling distance

$N(t)$ = ridership onboard i at time t

χe = primary fossil fuel consumption factor of electricity (MJ/kWh)

δe = emission factor ($kgCO_{2e}$/kWh) of electricity

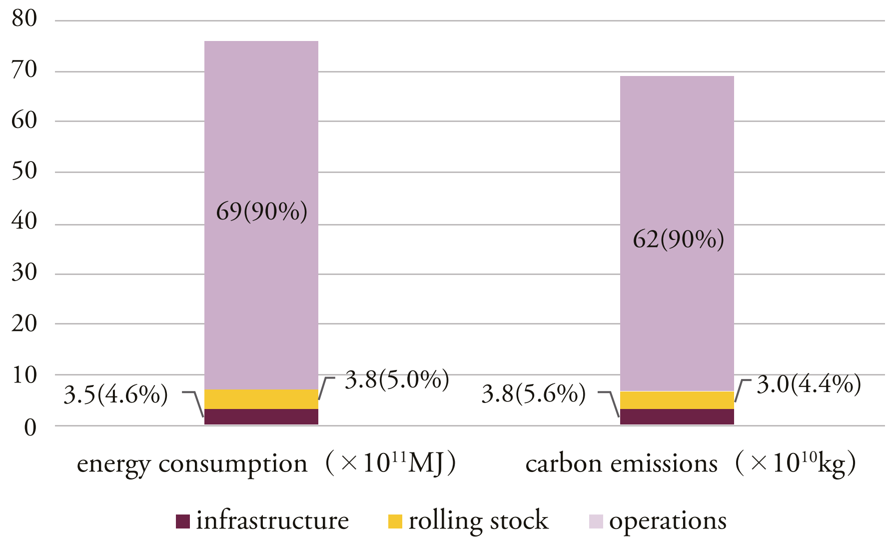
With the current energy mix (60 % coal) and power structure (70 % coal-fired electricity) in China as shown in **Table 11** and **Figure 5**, the operational cycle also contributes around 90 % of energy consumption and carbon emissions, while the infrastructure and rolling stock cycles contribute 5 % each.

If the result above are divided by the total passenger departures, the following LCA unit HSR service is achieved: energy consumption of 0.423 MJ/pkm and GHG emissions of 0.0384 $kgCO_{2e}$/pkm.

Table 11 Case Analysis: HSR Lifecycle Energy Consumption and GHG emissions (Beijing-Shanghai HSR: Construction Phase and 100-year Operational Phase)

	Unit	Cycle			Total
		Infrastructure	Rolling Stock	Operations	
Energy Consumption	MJ	3.50×10^{11}	3.80×10^{11}	6.88×10^{12}	7.58×10^{12}
Carbon Emissions	$kgCO_{2e}$	3.87×10^{10}	3.02×10^{10}	6.22×10^{11}	6.93×10^{11}
Share of Energy Consumption	%	4.6	4.99	90.41	100
Share of Carbon Emissions	%	5.61	4.37	90.02	100

Figure 5 Beijing-Shanghai HSR: Lifecycle Energy Consumption and Carbon Emissions



The study also found that with higher shares of clean energy in the power mix, and lower consumption and emission factors of electricity, the energy consumption and carbon emissions throughout the HSR lifecycle exhibit a significant decline.

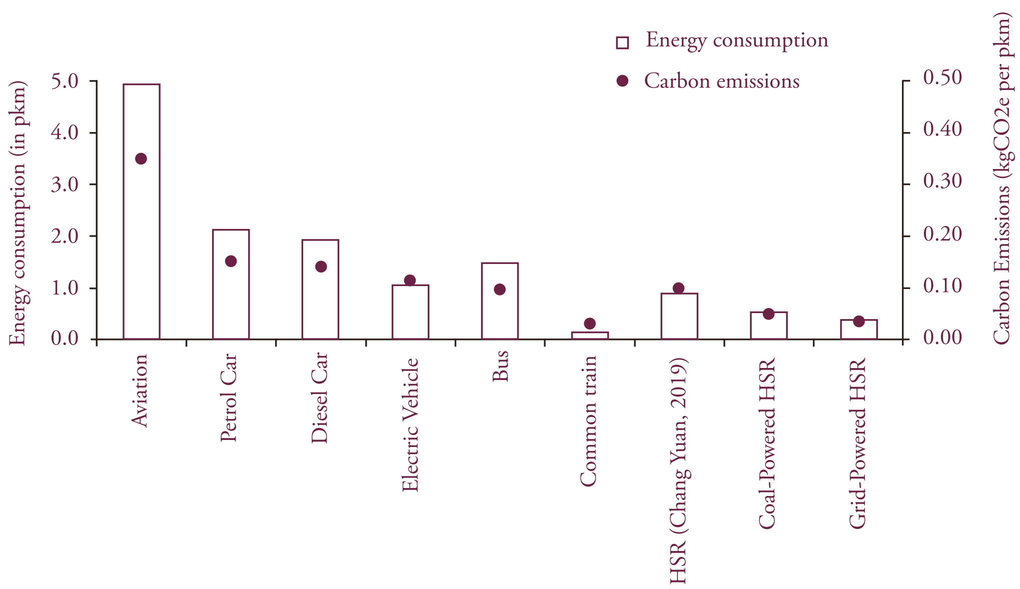
In parallel to an increasing occupancy rate, the energy consumption and carbon emissions per unit of service follow an inverse decline. Notably, occupancy affects the results greatly at a lower level and only moderately above levels of 80 %. When HSR runs at a low occupancy rate (<40 %) for an extended period, it is difficult to achieve the expected performance of energy saving and emission reduction; for occupancy rates above 90 %, the marginal benefit of higher occupancy is also limited.

3.4 Comparison: Carbon Emissions of Other Transportation Modes

Figure 6 shows the energy consumption and GHG emissions of different transportation modes based on the volume of transportation services. To achieve the same transport service (pkm), the carbon emissions of HSR are 0.10, 0.24, 0.26, 0.32, and 0.38 times that of aviation, petrol and diesel cars, EV, and buses respectively, indicating HSR advantages in energy saving and carbon reduction.

Such benefits of HSR are related to its high passenger capacity and energy conversion efficiency. Yet, the energy consumption per unit passenger turnover of HSR is significantly higher than that of regular trains because of its speed. Consequently, its carbon emission levels are relatively close to regular trains powered by internal combustion engine use fossil fuels, with higher energy consumption coefficient per unit of GDP.[76, 77,78 , 79, 80, 81]

Figure 6 Lifecycle Energy Consumption and Carbon Emissions of Different Transport Modes



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◆ Chapter IV ◆

Conclusions and Policy Recommendations

4.1 Review of HSR Development and Recommendations

The rapid expansion of the HSR network in China has strongly benefited people's mobility and strengthened inter-city transportation links. The expanded mobility offer has fostered socio-economic development, whilst simultaneously resulting in an ecological and environmental footprint, which should be analysed in depth. Based on the present study findings, a few observations and subsequent policy recommendations for HSR development can be made.

Detailed planning and continuous policy adaptation has ensured steady development of HSR in China. With the network-based system, HSR has become integrated with regular railway and urban transportation for higher utilisation. Particularly long-term planning is here key to secure the continuity and successful implementation of HSR construction projects.[82] Relevant measures should address an overall expansion of the HSR network, optimisation of connectivity and HSR accessibility, enlargement of HSR coverage area, higher efficiency and vehicle modernisation.

The burgeoning HSR has restructured the landscape of the transportation market of passenger transport by road, rail and air. The HSR development is anchored in the passenger market segment, featuring high passenger flow and medium traveling distance with advantages of punctuality, frequency and speed achieved by successful management, technologies, and services. The range of traveling distance with the largest crowding-out effect and modal shift for buses, regular trains and airplanes from HSR is 100-300 km, 300-700 km, and 700-1,000 km, respectively, within which a preference for HSR is observed for most travelers. Meanwhile, the competition between HSR and air travel is fierce in the 500-1,500 km range, exemplified by the distance from Berlin to Munich (around 600 km) and Berlin to Paris (around 1,110 km).

HSR fares, subject to government guidance and regulation in China, have remained relatively low. The rapid rise of HSR passengers in the past decade has reflected its growing popularity among many Chinese travelers. Future HSR price adjustments should consider the ideal point that ensures both profitability and competitiveness over other transportation modes, which must be targeted in order to maintain the current ridership of HSR. In the meantime, a tiered pricing of HSR and regular railway is needed to satisfy different traveling demands.[83] Furthermore, train timetables should be adapted to local conditions to increase the HSR occupancy rate: A high occupancy rate must be ensured to increase HSR efficiency, match supply and demand, and realise its energy-saving as well as emission reduction potentials.

[82] Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. China's High-Speed Rail Development. International Development in Focus. Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

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HSR has produced both direct and indirect economic benefits, such as generating new demand for business and tourism travels, as well as transport convenience and economic interactions with larger cities for small and medium-sized cities. In the context of large-scale government investment projects, HSR is a major booster to GDP and the prosperity of related industries for its contribution to employment rate, income level and the tourism market. In addition, HSR connections in remote areas also catalyse efforts in poverty alleviation.

HSR technologies have proven effective in saving energy and reducing emission in the railway sector, thereby fostering an overall green transportation network. Meanwhile, further analyses and intervention measures are necessary to reduce potential risks in relation to environmental protection, soil and water utilisation. Importantly, the optimisation of power structures and provision of a cleaner electricity mix are crucial to enhance the HSR energy conservation and emission reduction potentials, utilising electrification for the low-carbon development of the transportation sector in China.

4.2 Summary: HSR-Air Substitution

The opening of new HSR lines between 2008 and 2017 has shown a clear negative impact of HSR on domestic aviation with the overall number of flights and air travelers lowered by 28.7 % and 31.8 % respectively. The replacement of aviation by HSR can shrink the demand for air transportation, thus contributing to reducing China's greenhouse gas emissions in the transportation sector.

The competitiveness of HSR is captured by travel time, with the peak being within 4 hours, within which a strong impact is seen on competing civil aviation by reducing the number of flights and flight passengers by 74.2 % and 82.5 %. For rail travel duration within 6 hours or 1,400 km, there is still a strong substitution effect. Such impact of HSR declines as travel time further increases, with little consequence to domestic flights in HSR trips exceeding 8 hours.

With the inclusion of an additional 69 airports, the eight vertical and eight horizontal corridors will further impact another 834 air routes. The HSR-air replacement rate increases by another 8.8 % when future speeding-up of certain HSR lines is factored in. After HSR connectivity in cities with over 500,000 people is achieved, the HSR system will cover almost all domestic airports, thus potentially replacing 20% of the air travel market.

4.3 Summary: Lifecycle-based Analysis on Carbon Emissions of HSR

By calculating the energy consumption and carbon emissions of different phases including infrastructure, manufacturing and operations throughout the lifecycle of HSR using the LCA model, with the example of the HSR line Beijing-Shanghai, the following conclusions can be reached.

With the current energy and electricity structure in China, HSR produces significant benefits of energy conservation and emission reduction, which shows the primary fossil fuel consumption of HSR to be 0.08, 0.19, 0.21, 0.37 and 0.27 times while GHG emissions to be 0.10, 0.24, 0.26, 0.32 and 0.38 times that of airplanes, petrol and diesel cars, EV and buses, respectively.

The electricity mix and occupancy rate are the largest impact factors of energy consumption and GHG emissions of HSR. For the HSR line Beijing – Shanghai, 90 % of energy consumption and GHG emissions stem from its operational cycle, in particular due to the electricity used in train operations. The cleaner the energy and the higher the occupancy, the lower the energy consumption and GHG emissions.

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Figure 1 Operating Mileage and Passenger Turnover of HSR in China (National Bureau of Statistics. China Statistical Yearbook 2020.

Figure 2 Own illustration based on: HSR Network in China (2008 vs. 2020), Lawrence, Martha, Richard Bullock, and Ziming Liu. 2019. China's High-Speed Rail Development. International Development in Focus. Washington, DC: World Bank. doi:10.1596/978-1-4648-1425-9. License: Creative Commons Attribution CC BY 3.0 IGO.

Figure 3 Own illustration based on: HSR Planning in China: eight vertical and eight horizontal corridors (2016~2030), https://www.sohu.com/a/446657295_682294)

Figure 4 HSR Lifecycle: Cycle Division (created by author)

Figure 5 Beijing-Shanghai HSR: Lifecycle Energy Consumption and Carbon Emissions (estimated by author)

Figure 6 Lifecycle Energy Consumption and Carbon Emissions of Different Transport Modes (estimated by author)

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn und Eschborn

GIZ in China
Tayuan Diplomatic Office Building 2-5
14 Liangmahe South Street, Chaoyang District
100600 Beijing, P. R. China
T +86 (0)10 8527 5589
F +86 (0)10 8527 5591
E info@giz.de
I www.giz.de
I www.transition-china.org/mobility