High-Speed Rail and Urban Green Productivity: The Mediating Role of Climatic Conditions in China

Yunpeng Sun*

School of Economics, Tianjin University of Commerce, Tianjin, China

tjwade3@126.com

Asif Razzaq*

School of Management and Economics, Dalian University of Technology, Dalian, China

Department of Business Administration, ILMA University, Karachi, Pakistan

asifrazzaq@mail.dlut.edu.cn

Renatas Kizys

Southampton Business School, University of Southampton, UK

R.Kizys@soton.ac.uk

Qun Bao

School of Economics, Nankai University, Tianjin, China

baoqun@nankai.edu.cn

* Corresponding Authors

Author Biography

Dr. Yunpeng Sun is an Associate Professor at the School of Economics, Tianjin University of Commerce, Tianjin, PR China. His area of research is green finance, carbon neutrality, sustainability, climate change, green innovation, and financial markets. He published several papers in reputed journals such as the Journal of Environmental Management, Sustainable Development, Resources Policy, and Renewable Energy. He has many highly cited papers (top 1%) and hot papers (top 0.1%) in 2021 and 2022.

Dr. Asif Razzaq is a Ph.D. researcher at the School of Economics and Management, Dalian University of Technology. His area of interest in foreign direct investment, climate technology, and environmental sustainability. He mainly focuses on foreign investment and published in reputed SSCI/SCI journals such as Technology forecasting and social change, Business Strategy and the Environment, Journal of Environmental Management, Technology in Society, Sustainable Development, Resources Policy, and Environmental Research. Moreover, he has published over 50 research articles in reputed International Journals with 1800+ citations and an H-Index of 25. He is also the guest editor and reviewer of many SSCI/SCI International Journals. He has many highly cited papers (top 1%) and hot papers (top 0.1%) in 2020 and 2021.

Dr. Renatas Kizys is an Associate Professor at the Southampton Business School, University of Southampton, UK. His area of research is financial markets and policy. He published several papers in reputed journals such as the International Review of Finance, Journal of Financial Markets, Journal of Banking and Finance, and Regional Policy.

Dr. Qun Bao is a Professor in Economics at the School of Economics, Nankai University, Tianjin, PR China. He published several papers in reputed SSCI/SCI journals such as Journal of Business Research and Journal of Business Economics and Management.

Credit Author Statement

Yunpeng Sun: Data, methodology, empirical results, writing, drafting-Original draft

Asif Razzaq: Conceptualizing, writing, drafting-Original draft

Renatas Kizys : Supervision, reviewing, and editing

Qun Bao : Reviewing and editing

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Abstract

Climate change has become a global challenge to the economy and society, highlighting the urgent need for effective policy interventions. Green total factor productivity (GTFP) is a *sine qua non* for an environmental-friendly and sustainable economy. Therefore, this study investigates the causal relationship between the High-Speed Rail (HSR) and GTFP in a panel of 277 Chinese prefecture-level cities observed from 2003 to 2016. Using the Difference-in-Differences (DiD) approach, we demonstrate that the HSR opening has significantly increased urban GTFP. Furthermore, we explore the channels of the observed positive relationship between the HSR opening and urban GTFP. Specifically, we shed light on the mediating role of climatic conditions, air pollution, and factor agglomeration in the relationship between the HSR opening and GTFP. The results show that climatic conditions significantly mediate this relationship. HSR opening leads to lower pollution and more favourable climatic conditions. Improved climatic conditions drive talent gathering, investment gathering, and green technology concentration, which translate into higher GTFP. Government policies that create favourable climatic conditions to attract green investments in human and physical capital and stimulate green innovations can translate into higher GTFP.

Keywords: High-Speed Rail, Urban Green Total Factor Productivity, Climatic conditions, Air Pollution, Factor Agglomeration, China

1. Introduction

The expansion of eco-development and industrialisation worldwide strains the environment, triggering adverse environmental changes, and impairing the ecosystem. In the last 35 years, China has witnessed unprecedented growth, with an average annual growth rate of 9.8% (National Bureau of Statistics China, 2016). China's progress is primarily contingent on inputs and investment; a large portion of its growth relies on the industrial sector, making it the growth engine of the world economy (Azman-Saini, et al., 2010). However, its hasty development has triggered resource exhaustion and environmental degradation. Due to rapidly worsening environmental issues, the Chinese economy has focused on mitigating such hazards by gradually shifting from 'high-speed progress' to 'high-quality development' initiatives, which are prerequisites for the economy's long-term growth (Wen et al., 2021; Razzaq et al. 2022).

High industrial productivity and efficient resource utilisation are the key pillars of China's green and sustainable growth strategy (Luo et al., 2019). The Chinese industry faces challenges and competition driven by worldwide green industrial innovation. In this light, the country needs a sustainable development model that uses resources efficiently and improves the environment while enhancing industrial competitiveness (Irfan et al., 2022). The concept of 'green growth' is a short-term strategy to accomplish the 8^{th} goal of the Sustainable Development Goals (Hille et al., 2019; Suparjo et al., 2021). China strongly endorses a pollution-free green economy and has become an 'ecological civilisation' in recent years. In July 2016, under the '13th Five-Year Plan', China delivered the 'industrial green development plan (2016–2020)', a guideline for green industrial development. China has made tremendous improvements in green technology development (Li & Lin, 2017; Wang & Li, 2020; Zhu et al., 2021). It has a leading edge in green technology growth, notably in the areas of water disposal and wastewater treatment, photovoltaic solar (PV) energy, illumination, chemical entities for synthetic drugs or pharmaceuticals, hybrid cars, and other technologies used in infrastructure development (Wang & Li, 2020; Zhu et al., 2021). GTFP, also known as green technology innovation (GTI) (Yang et al., 2021), combines resource consumption (natural inputs) and ecological pollution (unwanted output) into the conventional Total Factor Productivity (TFP) concept in the context of green and sustainable production. Concretely, GTFP relates to environment-friendly innovative technologies for processes and products, considering the economic benefits induced by technological innovation and the environmental profits of clean energy and reduced emissions (Zhang et al., 2016; Gozgor, 2016,2018). It pursues a 'win-win' development and growth model for the environment and economy (Guo et al., 2018; Lin and Ma, 2022).

One of the critical drivers of high-quality, sustainable development in China is the growing investment in transportation infrastructure, such as the High-Speed Rail (HSR), which was put into operation in 2008.[1] The HSR facilitates the flow of capital, information, talent (skilled labour), and technology, which boosts production factors' geographical mobility. Between 2008 and 2018, the number of prefecture-level cities grew from 57 to 215. Similarly, by the end of 2018, 92 HSR lines were fully operational, with an improved mileage of approximately 30,000 km. In line with the '13th Five-year Railway Development Plan', the HSR network is estimated to further expand a further 3,700 km, reaching a total of 38,000 km by 2025, linking each provincial capital city to other medium-sized and large cities, and covering a population of approximately 500,000. Our study examines the impact of an HSR opening on GTFP in prefecture-level cities and strives to explore the channels of the HSR opening-GTFP nexus.

Not does investment in transportation infrastructure only drive sustainable economic development, but it also boosts firm productivity and efficiency (Zou et al., 2021), promotes economic growth (Donaldson & Hornbeck, 2016; Banerjee et al., 2020), increases regional trade integration and boosts national income through spillover effects (Boarnet, 1998). It also accelerates the flow of goods, capital, and talent between cities (Li & Chan, 2021) and improves labour allocation through mobility (Chen et al., 2021), stimulates urban employment growth, and increases the degree of specialisation (Zou et al., 2021). The expansion of the HSR network has reduced income inequalities across regions, fostering regional economic integration in China (Fu et al., 2012). Furthermore, the HSR enhances labour productivity and economic efficiency within the HSR corridor and between station areas (Carbo et al., 2019). The rapid development of China's HSR has reduced commuting times, increased travel efficacy, and improved economic and personnel communication between cities and regions.

Traditional transportation infrastructure deteriorates climatic conditions by increasing hazardous emissions. Thus, reducing transportation emissions is paramount to mitigating climate change. Modern transportation, such as the HSR, cuts vehicle emissions by one-

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[1] The International Union of Railways defines the HSR as a railway whose current lines are renovated and reach a speed of up to 200 km/h, or whose newly built lines can reach a speed of more than 250 km/h.

third (Wolfram & Lutsey, 2016). Reducing harmful emissions in the atmosphere improves the climate (temperature and sunshine duration) and mediates an increase in GTFP. Favourable climatic conditions support agriculture, manufacturing, and industrial production and help to enhance productivity. By contrast, variability in short-term (particularly drought) and long-term climatic conditions have adverse effects on agricultural productivity (Burke and Emerick, 2016; Hughes & Lawson, 2017; Chambers et al., 2020; Njuki et al., 2020; Donadelli et al., 2021). Although the degree to which a decline in the volume of road traffic resulting from the opening of new HSR routes mitigates climatic conditions is uncertain, low carbonisation in the transport infrastructure is critical to any pollution mitigation strategy. The International Energy Agency (IEA) estimates that between 2000 and 2018, the transport infrastructure only accounted for approximately 24% of global CO_2 emissions, which grew over time, contributing to climate change. An astounding 96% of final global energy consumption related to transportation–by rail, road, water, and air–is fossil-fuel based (China Communications & Transportation Association). Therefore, the HSR opening may significantly reduce air pollution (Lin et al., 2021).

The CO_2 mitigating effect stems primarily from the integration of HSR transportation with the conventional railway system, which consumes more energy and time. The HSR helps to alleviate these issues, improving climatic conditions and productivity. In general, green innovations drive long-term productivity and sustainable growth, and thus may be considered a crucial sustainability factor (Rezende et al., 2019; Aldieri et al., 2020; Cunningham and Kwakkel, 2011). However, the relationship between the HSR and GTFP has escaped academic scrutiny. To the best of our knowledge, this study is the first to address the HSR opening-GTFP nexus. Our main academic contribution is to demystify the mechanism that drives the impact of the HSR opening on GTFP. Also, research into whether and, if so, how the HSR influences GTFP informs sustainable growth policies and strategies.

This study addresses the following research questions. First, has the opening of the HSR promoted GTFP growth in China? Second, does air pollution drive the relation between the HSR opening and GTFP? Third, do climatic conditions (temperature, humidity, and sunshine duration) significantly mediate the relationship between the HSR opening and GTFP? Fourth, what is the role of factor agglomeration in mediating the relationship between the HSR opening and GTFP?

Our research shows that the mechanism that drives the relation between the HSR opening and GTFP is multifaceted. Our contribution is five-fold. Our first contribution is to study whether and, if so, how the HSR opening influences GTFP. By scrutinising the effect of the HSR opening on GTFP, we add to the literature on the determinants of GTFP. Our second contribution is to examine if lower air pollution can mediate the relation between the HSR opening on GTFP. In this regard, our research varies from Zhang & Song (2002), who seek to ascertain if tax rebates for energy conservation and environmental protection can lead to superior economic and environmental performance through improved TFP. Our third contribution is to ascertain if favourable climatic conditions (temperature and sunshine duration) can mediate the effect of the HSR opening on GTFP. Fourth, differently from Song et al. (2022), who explore the role of environmental regulation in stimulating green innovation and TFP, we scrutinise the effects of climatic conditions induced by the HSR network expansion on factor agglomeration (i.e., green technology concentration, talent gathering, and investment gathering) and GTFP. Our fifth contribution is to shed light on the multidimensional and heterogeneous impact of the HSR on GTFP. Taken together, our study adds considerable value to the body of research into the green and sustainable growth effects of the HSR in China, which provides meaningful policy implications and strategic considerations for the Chinese government.

Our sample consists of 277 prefecture-level cities observed from 2003 to 2016. We employ a Difference-in-Differences (DID) approach to investigate whether the HSR network expansion has a significant association with GTFP. We construct the Global Malmquist-Luenberger (GML) index for measuring GTFP in China. Our results are as follows. First, our results show that the HSR opening exerts a positive effect on GTFP. Second, we find that climatic conditions significantly mediate the relationship between the HSR opening and GTFP. Third, a more granular analysis demonstrates that the HSR network expansion is instrumental in lower air pollution, which translates into more favourable climatic conditions. Fourth, our study demonstrates that the improved climatic conditions stimulate factor agglomeration (talent gathering, investment gathering, and green technology concentration), which leads to higher GTFP. This finding partly echoes Yu (2022), who documents a positive association between Internet development and industrial GTFP. Further, when the HSR opening indicator is replaced with the city's network connection breadth and network centrality measures, the mediation effects of climatic conditions remain qualitatively intact.

This paper is organised as follows. Section 2 provides an exhaustive review of the related literature to support our research argument. In this section, we also outline the hypotheses. In Section 3, we lay out the methodology. In Section 4 we present and discuss our research findings. In Section 5, we conclude.

2. Literature Review and Hypothesis Development

Studies typically use labour, capital, and output to measure total factor productivity (TFP) (Chen, 2011; Wu et al., 2017). However, the traditional TFP measure fails to reflect environmental restraints. Unlike TFP, GTFP accounts for the ecological component that includes undesirable outputs in the model (Emrouznejad & Yang, 2018). For instance, Kumar (2006) and Mahlberg and Sahoo (2011) include CO_2 emissions into the TFP model and examine GTFP for various countries. Likewise, Zhang et al. (2011) incorporate different undesirable environmental outputs in TFP to measure GTFP in various provinces of China. GTFP is measured employing parametric and non-parametric approaches. A parametric approach (Li et al., 2017) is simple but requires advanced functional form assumptions. Non-parametric approaches comprise data envelopment analysis (Chen et al., 2015), the Malmquist index (Greer, 2008), the directional distance function (Chung et al., 1997), the Malmquist-Luenberger (ML) index, and the Slack-Based measure (SBM) (Li and Tao, 2011; Li et al., 2013). These approaches do not entail a functional form and a decision-making unit. An advantage of the Global Malmquist-Luenberger (GML) index may avoid the possible linear programming infeasibility.

Technological progress in transportation (such as the HSR) has multidimensional effects on GTFP in different regions. Technological progress in the vehicle sector and technical gaps are the critical factors that stimulate GTFP (Feng & Huang, 2018), with heterogeneous impacts across regions. Labor-biased technical advancement can efficiently expand GTFP (Wang et al., 2018). Miao et al. (2020) specified that research and development (R&D) in green technologies enhances the productivity of natural resource utilisation, profoundly affecting GTFP.

The effect of opening the HSR on the economy has attracted scholarly attention in recent times (Verma et al., 2013, Jia et al., 2017). Enhancing total productivity and better utilisation of resources are primary elements of China's green and sustainable growth strategy (Zhang et al., 2019). Carbo et al. (2019) evaluate the economic influence of the HSR between Madrid and Barcelona. They show that the HSR enhances labour efficiency and increases total factor productivity and economic turnout in the HSR corridor. However, the HSR contributes to shifting economic activities from remote areas to urban centers, which results in unbalanced regional development and prevents the economic development of non-central cities (Qin, 2017).

Holl and Mariotti (2017) consider the effect of Spanish superhighway development on the productivity of metropolitan and rural logistics firms. They observe that transportation developments encourage growth of urban logistics firms. While this is not the case for rural logistics firms, they boost economic activities, increase local population concentration, and affect firms' productivity through agglomeration gains (Holl, 2016). Likewise, establishing a new road structure benefits labour productivity and TFP (Gibbons et al., 2019). Nevertheless, very few studies have examined the association between the HSR and TFP, with special emphasis on GTFP (Wang et al., 2021; Wang et al., 2022).

In China, TFP has remarkably improved after the HSR opening. In this regard, previous research examines the heterogeneity of GTFP across different cities of China. The causal relation of the HSR to regional ecology unfolds via three channels. Firstly, HSR's influence on the climate depends on life-cycle analysis (Chester & Horvath, 2010). Secondly, the effect of the HSR on the climate is related to other transportation modes and factors (energy consumption, transportation distance, capacity, noise, and land take) (Janic, 2003; Albalate & Bel, 2012). Thirdly, previous research has examined the effect of the HSR on ecological pollution, such as carbon footprint, biodiversity, and industrial structure changes (Tsai, 2017; Cornet et al., 2018; Yang et al., 2019).

Understanding the shifts from road to rail transportation is critical in gauging the impact of HSR infrastructure on the environment and energy utilisation. However, few studies have explored the direct effects of the HSR on road traffic, and scant research has been conducted on the associated environmental co-benefits. Extant studies have mostly emphasised the impact of the HSR opening on local pollutants, and most of them found significant adverse effects (Baron et al., 2011; Li et al., 2020; Zhu et al., 2020), while others did not find any significant effects (Chester & Horvath, 2010; Lin et al., 2019). Remarkably, the HSR's impact on GTFP has not been previously examined by considering climatic conditions as a mediator.

Our study aims to bridge several gaps in the literature. First, research that seeks to evaluate the impact of the HSR on GTFP is limited. Our study provides new insights in this regard. Second, in the recent research stream exploring the relationship between transportation infrastructure and firm factor productivity, only a few studies have focused on the mediating effects of the environment and climatic conditions considering the HSR-GTFP nexus. In addition, our research evaluates the mediating role of the mobility of production factors, such as factor agglomeration.

The literature considers GTI as one of the critical priorities of the Chinese government in its national innovation strategy to fight the global environmental crisis (pollution, overpopulation, global warming, waste disposal, loss of biodiversity, ocean acidification, deforestation, and ozone layer depletion). GTI is an essential area of focus for China's manufacturing sector to balance the need of the society, economy, and environment. Improving GTI growth will help protect the environment while achieving social and economic advancement.

Transportation infrastructure is a pillar of China's regional modernisation system and network. Advanced transportation infrastructure helps achieve a developed and innovative network, improving accessibility (Fritsch & Slavtchev, 2011). The HSR features a broad-regional span, high speed, and high density in an innovative and advanced transportation system. It is more rapid than the old rail and highway system and extensively uses the three-level 'China Train Control System (CTCS-3)', which can achieve a maximum speed of 350 km/h. In contrast, the maximum speed of old trains does not exceed 250 km/h, and the maximum speed of the highway is 120 km/h. The HSR primarily improves long-distance transportation. It operates between and across many cities. The HSR is a large-scale transportation infrastructure service that facilitates the flow of information, capital, and labour among cities (Zhao et al., 2021). The HSR network promotes the movement of people, goods, knowledge, and information (production factors) between cities (Dong et al., 2020). Compared to traditional means of transportation, the HSR directly affects the flow of capital, improves the effectiveness of labour allocation, and supports knowledge diffusion with profound economic consequences. Knowledge is the foundation of scientific and technical innovation, but distance may hinder it (Agrawal et al., 2017). The HSR facilitates the movement of skilled workers between cities, providing new resources for innovation and expanding market size (Gao & Zheng, 2020).

The impact of the HSR on TFP primarily depends on the following aspects. Firstly, the opening of the HSR strengthens economic bonding among cities by reducing travel time, decreasing costs, and enhancing productivity, ultimately promoting a sustainable economy (Yang et al., 2019). Secondly, it encourages the exchange of innovation factors, supporting innovation and knowledge diffusion. Production factors carry and transmit knowledge between regions, inducing a knowledge acceleration path (Bian et al., 2019).

HSR services boost mobility of talent, skills, and innovation. By virtue of lower travel costs associated with HSR and increased time value, the HSR breaks down obstacles to factor mobility instigated by low transportation connectivity (Chen & Haynes, 2017). This effect is more substantial for people with higher innovative abilities and skills (Huang & Wang, 2020). Compared to traditional production factors, a high-quality workforce is more likely to export knowledge and technological innovations. Hence, this discussion crystallises into the following hypothesis:

Hypothesis 1: Access to HSR services is associated with an increase in urban GTFP.

The HSR exerts direct and indirect effects on climate (temperature, humidity, and sunshine duration). Firstly, as a clean and efficient transportation mode, which substitutes conventional vehicles and planes, the HSR has direct climatic consequences. It utilises less energy and produces less than half of the carbon and silicon emissions while carrying the same number of commuters (Yang et al., 2019). Secondly, the HSR is more efficient and operates at higher speeds and densities than conventional rail transport (Chai et al., 2018). Consequently, the HSR can restructure regional economic growth by achieving time-space compression. It comprises a set of processes that shorten relative distances between places (i.e., as measured in terms of travel time or cost), with indirect ecological impacts on regional climate (Tsai, 2017; Jia et al., 2021).

Temperatures have significantly risen in China during the past few years; therefore, productivity needs to account for such temperature increases (Xiao et al., 2016). Excessive use of fertilisers and pesticides increases the temperature in agricultural countries such as China, adversely impacting the climate. However, with the help of modern technologies and plastic film products, rainwater is used at its maximum, which limits temperature rises. For instance, Van den Besselaar et al. (2015) find that sunlight dimming (brightening) partially decreases (increases) the temperature, thus affect the greenhouse gas (GHG)-induced warming. In turn, GTFP fluctuations are associated with climatic conditions. In this regard, Tao et al. (2006) argue that internal production factors and climatic factors drive fluctuations in GTFP. Similarly, advanced technological innovations, such as the HSR, may help to improve the climate, which enhances GTFP. Stable climatic conditions are a prerequisite for better productivity (Feng et al., 2020). Hence, we propose the following hypothesis:

Hypothesis 2: The HSR leads to an increase in urban GTFP by improving climatic conditions (temperature, humidity, and sunshine duration).

Emissions from efficient power trains reduce CO_2 in the atmosphere using electric power. As aforementioned, modern and improved technologies like the HSR cut vehicle emissions by one-third (Wolfram & Lutsey, 2016). Lower harmful emissions in the atmosphere improve the climate. Reducing the redundancy of input factors in production processes is another effective method for lowering CO_2 emissions and temperatures, which enhances GTFP. Moreover, a higher GTFP can be attained by reducing the redundancy of unwanted output (CO_2, SO_2, and $PM_{2.5}$ emissions) (Feng et al., 2020). To reduce CO_2 emissions, China's manufacturing industry has been subjected to various environmental laws and regulations. Environmental laws have effectively reduced pollutant emissions, supporting technological progress and factor productivity (Shi & Li, 2019). Hence, we propose the following hypothesis:

Hypothesis 3: The HSR inhibits air pollution, which improves climatic conditions.

Transportation advancements can make locations appealing to residents, workers, and businesses, increasing investment and land-use changes. These variations may have a significant impact on agglomeration and factor productivity. They may enable economies of scale and specialisation gains. Transportation improvements that allow for greater and more efficient labour force participation may also change the labour supply. However, jobs are created in some areas and lost in others. Furthermore, in most cases, commuters using new travel modes, such as the HSR, transfer traffic from other transport modes serving the same destination. Even though users benefit from the change, this shift impacts resources less than HSR routes in new areas (Shen & Peng, 2021).

A modified transportation system has both trade creation and trade diversion effects. Furthermore, the HSR uses information systems to regulate and manage operations and refine prices to meet revenue targets. This aspect is especially critical when the high-speed system shares infrastructure with other rail services. Factor agglomeration (talent gathering, investment gathering, and green technology concentration) can stimulate green development by expanding scientific innovation (Xie & Li, 2021), optimising the industrial structure, and strengthening government intervention. Previous research has shown that factor agglomeration may reduce regional pollution, accelerate environmental innovation, increase energy utilisation efficiency, and reduce polluting emissions through the spillover effect of green knowledge, environmental protection resource sharing, and equivalent effects (Shen & Peng, 2021). Previous heterogeneity analyses have revealed that factor agglomeration has a more decisive role in stimulating green development in areas where the level of GHG emissions is very low, the climate is conducive to life, the degree of resource dependence is low, and the degree of factor agglomeration is high (Xie & Li, 2021). Therefore, the urban temperature may inhibit talent, investment, and GTI agglomeration, while improved sunshine duration promotes agglomeration and improves TFGP. Hence, we propose the following hypothesis:

Hypothesis 4: Climatic conditions increase urban GTFP through talent gathering, investment gathering, and green technology concentration.

3. Methodology and Data

3.1 Data Selection

Table 1 reports the descriptive statistics of the HSR and GTFP indicators for prefecture-level cities in China from 2003 to 2016 (see Table A1). We gathered data from the China City Statistical Yearbooks, the Railway Corporation, and news reports or announcements of the National Railway Administration. We also obtained data from the Atmospheric Composition Analysis Group at Dalhousie University in Canada, meteorological station data within the jurisdiction of prefecture-level cities, and patent data from the State Intellectual Property Office of China (the Appendix provides a detailed description of the data sources). Due to missing data, we included 277 cities in the analysis. To avoid heteroscedasticity, we used the logarithmic form of the variables.

Table 1. Descriptive Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
$GTFP$	3,878	1.005	0.032	0.828	1.389
US	3,878	48.90	73.13	4.05	986.90
GI	3,878	213.44	400.48	3.31	692.07
GDP	3,878	32937	28965	99	467749
ES	3,878	37.95	72.73	8.580	4533

TA	3,878	2437	7143	2	102205
CO_2	3,878	24.70	22.85	1.529	230.7
SO_2	3,878	6.57	8.52	2	152.63
$PM_{2.5}$	3,878	36.85	16.50	2.303	90.86
$TEMP$	3,878	14.93	5.054	0	27
HUM	3,878	67.90	9.482	37	91
SUN	3,878	1978	503.2	598.4	3376
TG	3,878	0.884	1.054	0.010	5.370
IG	3,878	0.003	0.063	0.001	0.160
GT	3,878	0.004	0.032	0.001	0.141

GTFP assimilates the environmental pollution index within the index system of economic growth. It uses the TFP index to judge if a region's economic development adopts a long-term sustainable approach or produces emissions first and seeks mitigations later. We used the SBM-Data Envelope Analysis (DEA) method to calculate urban GTFP. DEA, first developed by Charnes et al. (1978), is a non-parametric method; hence, it does not require an input-output function. We obtained the GML index using the formula developed by Fukuyama and Weber (2009):

$$GML^{t,t+1}(X^t, Y^t, Z^t, X^{t+1}, Y^{t+1}, Z^{t+1} = \frac{1+S^{\to G}(X^t, Y^t, Z^t, g^X, g^Y, g^Z)}{1+S^{\to G}(X^{t+1}, Y^{t+1}, Z^{t+1}, g^X, g^Y, g^Z)} \quad (1)$$

where $S^{\to G}(X^t, Y^t, Z^t, g^X, g^Y, g^Z)$ represents the global SBM-directional distance function (DDF) based on non-radial and non-directional measurements. The directional distance function (DDF) seeks to expand the production possibilities and reduce pollution emissions. Doing so, it reflects the concept of sustainable development. We used the Malmquist-Luenberger (ML) productivity index to calculate China's urban GTFP (Zhang & Tan, 2016; Li et al., 2021a, b). We employ the GML index to measure the periodic change between t and t+1. If the GML rate is greater than one, GTFP increases year on year. If the GML index equals one, GTFP is stationary, and if the GML index is less than one, GTFP decreases year on year. It is important to note that the GML index reflects the growth rate of GTFP. Hence, we need to make some regression assumptions.

The first core explanatory variable is HSR opening ($TREAT_i \times AFTER_{it}$). We obtained data on the HSR from the Railway Corporation and news reports or announcements of the National Railway Administration for Chinese prefecture-level cities. We generated this variable as a dummy equal to one for the cities where the HSR is introduced, and zero otherwise.

The second core explanatory variable is HSR network (DC and CC). The HSR network reflects the different opening years of HSR lines. We used social network analysis to calculate cities' network connection breadth and network centrality within HSR operations. We addressed cities in the HSR network from the two perspectives mentioned above.

Next, this study resorted to Freeman indices (1977, 1978), such as degree centrality (DC) and closeness centrality (CC), commonly used to measure network node connectivity. These centrality measures served as the foundation for further investigation. We measured network connection breadth by degree centrality (DC) and network centrality by closeness centrality (CC) We expressed the DC of a node as the ratio of edges connected with the given node in a complex series of networks (Wang et al., 2014). Consequently, the DC criterion corresponds to the connections among nodes in an HSR network. In general, the DC distribution highlights the importance of nodes and reflects the topological characteristics of HSR complex networks. The DC of node i reflects its network accessibility. It is defined it as:

$$DC_{it} = \frac{k_{it}}{N-1} \tag{2}$$

where k_{it} represents the number of cities directly connected to city i in year t. $N-1$ is the maximum possible degree value of the node.

CC estimates how close a given node is to all other nodes in any network. A node's CC is the inverse of the average shortest distance between it and another node in a given network (Nieminen, 1974). The CC measures a node's proximity to all other nodes and reflects its connectivity in the network. The shorter the distance between a node and its neighbours, the higher its CC, and the easier the access to other nodes. We define the CC of node *i* as:

$$CC_{it} = \frac{1}{d_{it}} = \frac{N}{\sum_{j=1}^{N} d_{ijt}} \tag{3}$$

where d_{it} represents the average distance between node city i and other nodes in the network in year t.

In the regression analysis, we control for urban size (urban employed population), government intervention (fiscal expenditure), urban economic development level (per capita GDP), urban economic structure (proportion of tertiary industry), and technological advance (number of patent grants).

Previous studies have extensively examined the role of technical advances in sustainable development (Zhang & Vigni, 2021). After the Porter Hypothesis (PH) (Porter, 1991; Porter and Porter, 1995), the literature has established that well-designed regulation benefits a firm's economic performance, and may help firms overcome market failures, such as information asymmetry and control power problems, and boost innovation by reducing innovation costs and sponsoring innovative projects. These phenomena, in turn, increase resource allocation efficiency and product value, increasing productivity and improving environmental quality, ultimately increasing green productivity. Overall, previous research shows a positive impact of technological advances on GTFP (Lin and Nelson, 2017; Zang et al., 2020). This study uses patent grants to assess innovation ability to make its findings easily comparable to the results of previous studies (Dang & Motohashi, 2015; Song et al., 2017).

Large urban areas are more productive (Qiang, 2018). Therefore, urbanisation has a profound impact on GTFP. The allocation of resources between urban and rural areas may change due to urbanisation. Cities can supply machinery, seeds, and advanced technology to continuously improve TFP. However, urbanisation is often accompanied by large labour migration from rural to urban areas, occupation of farmland by urban construction, and environmental pollution caused by industrialisation (Nathaniel et al., 2021). These phenomena hinder the long-term development of GTFP in China.

The GDP per capita is referred to as the urban economic development level. It can reflect a city’s economic activity load per person and its economic activity scale. In theory, a better economic structure supports technology generalisation, allowing significant knowledge overflow and a critical external economy, resulting in higher GTFP (Lin & Chen, 2018; Xia & Xu, 2020). This study used GDP data obtained from China Statistical Yearbooks.

3.2 Methodology

3.2.1 Baseline Model

The DID method is typically used to determine causal effects. Following Sun et al. (2022), we used the DID method to identify the impact of HSR on GTFP in China. We consider the following panel data model:

$$lnGTFP_{it} = \alpha_0 + \alpha_1 TREAT_i \times AFTER_{it} + \theta' X_t + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

where *i* and *t* represent the city and year, respectively; $lnGTFP_{it}$ is the logarithm of GTFP in city i in year t; $TREAT_i \times AFTER_{it}$ indicates the HSR opening in the city i in year t; X_t is a vector of logarithmically transformed control variables comprising urban size (urban employed population), government intervention (fiscal expenditure), urban economic development level (GDP per capita), urban economic structure (proportion of tertiary industry), and technological advancement (number of patent grants). Further, μ_i is the city fixed effect, which controls unobserved city characteristics that do not vary over time; δ_t is the year fixed effect, which controls unobserved urban heterogeneity that varies over time, and ε_{it} is the idiosyncratic random disturbance term. Hypothesis 1 implies $\alpha_1 > 0$. In other words, after the city is connected to the HSR network, its urban GTFP rises.

3.2.2 Mediating Effect

To test Hypothesis 2-4, we adopt the three-step approach proposed by Baron and Kenny (1986), which aims to evaluate the role of mediating variables between the explanatory and dependent variables in a regression model. Rooted in social psychology, the concept of mediation can be generalised to multiple contexts, in which the importance of entities, organisms, or processes intervening between input (or stimulus) and output (or response) is underscored. Unlike moderation, where the causal relation varies as a function of the moderating variable, mediation aims to shed light on the generative mechanism through which the independent variable can influence the dependent variable (Baron and Kenny, 1986). In a nutshell, this approach consists of three steps, outlined below.

Step 1. The dependent/outcome variable Y is regressed on the independent variable X:

$$Y = AX + e_1, \tag{5}$$

where the estimate of A is expected to be significant.

Step 2. The mediator M is regressed on the independent variable X:

$$M = BX + e_2, \tag{6}$$

where the estimate of B is expected to take on values that are significantly different from zero.

Step 3. The dependent/outcome variable is regressed on both the independent variable X and the mediator variable M, as indicated in the following equation:

$$\square = CX + DM + e_3 \tag{7}$$

M is said to mediate between X and Y if a) D is significantly different from zero, and b) the effect of X on Y in the third-step regression, C, is smaller in absolute value and/or less significant than the effect of X on Y in the first-step step regression, A. The variable M is deemed a single, dominant mediator if C is reduced to 0 (Baron and Kenny, 1986).

Hypothesis 2 implies that the climate variables (temperature, humidity, sunshine duration) effectively mediate the relation between access to HSR services and urban GTFP. We seek to ascertain if the HSR opening (see, e.g., Figure 1) can boost urban GTFP through climatic variables. Equation 4 (outlined previously) describes Step 1. In Step 2, we test the impact of the HSR on climatic variables (temperature, humidity, and sunshine duration), and we control for a vector of variables lnX_{it}:

$$lnCLIMATE_{it} = \beta_0 + \beta_1 TREAT_i \times AFTER_{it} + \beta_2{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{8}$$

Step 3 considers climatic conditions (temperature, humidity, and sunshine duration) in the baseline model:

$$lnGTFP_{it} = \gamma_0 + \gamma_1 TREAT_i \times AFTER_{it} + \gamma_2 lnCLIMATE_{it} + \gamma_3{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (6)$$

Turning to Hypothesis 3, Step 1 evaluates the effect of the HSR opening on the climate variables (temperature, humidity, and sunshine duration):

$$lnCLIMATE_{it} = \alpha_0 + \alpha_1 TREAT_i \times AFTER_{it} + \alpha_2{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (9)$$

Step 2 tests the impact of the HSR opening on air pollution (CO_2, SO_2, and $PM_{2.5}$):

$$lnAIRPOLLUTION_{it} = \beta_0 + \beta_1 TREAT_i \times AFTER_{it} + \beta_2{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (10)$$

Step 3 introduces air pollution (CO_2, SO_2, and $PM_{2.5}$) in the baseline model where climatic conditions (temperature, humidity, and sunshine duration) are the dependent variables:

$$lnCLIMATE_{it} = \gamma_0 + \gamma_1 TREAT_i \times AFTER_{it} + \gamma_2 lnAIRPOLLUTION_{it} + \gamma_3{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it}. \quad (11)$$

Finally, to test Hypothesis 4, we proceed as follows. Step 1 evaluates the effect of climatic conditions (temperature, humidity, and sunshine duration) on urban GTFP:

$$lnGTFP_{it} = \alpha_0 + \alpha_1 lnCLIMATE_{it} + \alpha_2{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (12)$$

In Step 2, we test if factor agglomeration (talent gathering, investment gathering, and green technology concentration) is driven by the climate variables (temperature and sunshine duration):

$$lnAGGLOMERATION_{it} = \beta_0 + \beta_1 lnCLIMATE_{it} + \beta_2{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (13)$$

In Step 3, we consider both factor agglomeration (talent gathering, investment gathering, and green technology concentration) and the climate variables:

$$lnGTFP_{it} = \gamma_0 + \gamma_1 lnCLIMATE_{it} + \gamma_2 lnAGGLOMERATION_{it} + \gamma_3{}' lnX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (14)$$

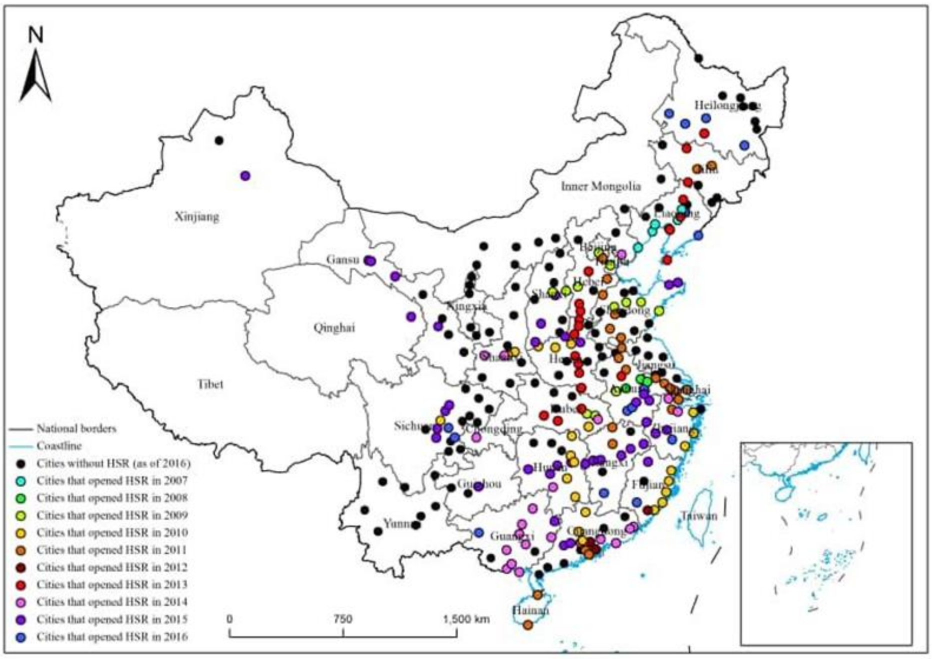

Figure 1. HSR Opening in Prefecture-level Cities

4. Results and Discussion

4.1 Baseline Model Results

After validating the parallel trend hypothesis, Table 3 reports the baseline results of the DID method. The coefficient of our primary explanatory variable, HSR, is positive and significant, indicating a positive relationship with GTFP. This result accords with Hypothesis 1. Specifically, the estimated coefficient of $TREAT \times AFTER$ is 0.0207; this means that the HSR opening leads to an increase in GTFP by 2.07% in cities connected by the HSR. Therefore, GTFP is significantly higher in the cities reached by the HSR than in other cities. In contrast, the coefficient estimates of US and ES are insignificant. Government interventions command a negative and significant effect, while GDP has a positive and significant effect on GTFP. This result indicates that GDP per capita is significantly higher in cities reached by the HSR (Liu & Li, 2017). The TA coefficient is negative and significant. Although technological improvement optimises the utilisation of resources by mitigating pollution, most Chinese cities are already fully developed, limiting further productivity advances.

Table 3. Baseline Results

Independent Variables	Dependent Variable： $lnGTFP$
$TREAT \times AFTER$	0.0207***
	（4.52）
$lnUS$	0.0014
	（0.21）
$lnGI$	-0.0189***
	（-4.28）
$lnGDP$	0.0151*
	（1.56）
$lnES$	-0.0078
	（-0.49）
$lnTA$	-0.0042**
	（-2.69）
Year fixed	YES
City fixed	YES
Observations	3878
R-squared	0.4663

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

The internal validity of the estimated model is confirmed via the parallel trend test (see Table OA1 in online Appendix). Our robustness analysis indicates noticeable geographical and urban-grade heterogeneity effects of HSR on urban GTFP (see Table OA2 in the online Appendix).

Using China's city level data, Li and Cheng (2022) apply DiD approach to study the influence of high-speed rail on urban carbon emission efficiency. Their findings indicate that high-speed rail can greatly increase the efficiency of urban carbon emission reduction. According to the heterogeneity results, non-resource-based major cities are more likely to benefit from high-speed rail's boosting effects on urban carbon emission efficiency. Additional examinations of the transmission mechanisms reveal that high-speed rail may enhance urban carbon emission effectiveness through technical advancement, structure optimization, tightening environmental laws, and lowering market segmentation. Likewise, Lau (2010) examines the factors influencing conditional convergence in China. The findings suggest that trade openness, infrastructure for transportation and telecommunication, and low inflation would support economic growth in China.

4.2 Mediating Effects

4.2.1 The Mediating Effects of Climatic Conditions

The HSR generates significant economic benefits with limited economic and environmental costs. The strong connection between climate change and the HSR provides a rationale for exploring climate conditions as a channel through which the HSR may affect GTFP. Since the HSR was found to influence urban GTFP, we now consider the mediating role of climate conditions (temperature, humidity, and sunshine duration). Table 4 shows that the opening of the HSR significantly reduces urban temperature ($lnTEMP$), but it increases urban humidity ($lnHUM$) and urban sunshine duration ($lnSUN$), as shown in columns 1-3. Results in columns 4–6 reveal the mediating role of climatic conditions in the relationship between the HSR opening and GTFP. The HSR can promote urban GTFP by reducing temperature and increasing urban sunshine duration. This is because the effects of the HSR opening are smaller in the third-step regression (0.0115, 0.0081, and 0.0093, see columns 4-6 of Table 4) than in the first-step regression (0.0207, see Table 3). Although the HSR increases air humidity, this variable does not mediate the relationship of interest. Innovative technologies and clean and environmentally friendly energy can minimise resource use and carbon emissions in manufacturing (Jin et al., 2019). Overall, the results lend partial support to Hypothesis 2.

Table 4. The Mediating Effects of the Climatic Conditions

Independent Variables	Dependent/Mediating Variables					
	$lnTEMP$	$lnHUM$	$lnSUN$	$lnGTFP$	$lnGTFP$	$lnGTFP$
	(1)	(2)	(3)	(4)	(5)	(6)
$TREAT \times AFTER$	-0.0112***	0.0104***	0.0121***	0.0115***	0.0081***	0.0093***
	(-5.21)	(5.30)	(4.89)	(5.33)	(3.68)	(4.47)
$lnTEMP$				-0.0117**		
				(-2.19)		
$lnHUM$					0.0086	
					(0.36)	
$lnSUN$						0.0089***
						(2.57)
$lnUS$	0.0138**	-0.0014	0.0031	0.0078	0.0052	0.0011
	(1.55)	(-0.53)	(0.32)	(0.56)	(0.29)	(0.23)

$lnGI$	0.0013	0.0059	-0.0414***	-0.0402***	-0.0103***	-0.0059
	(0.41)	(0.65)	(-4.51)	(-4.29)	(-5.27)	(-0.28)
$lnGDP$	0.0039	-0.0068	0.0122*	0.0059*	0.0025*	0.0055*
	(0.49)	(-0.64)	(1.59)	(1.69)	(1.79)	(1.83)
$lnES$	0.0014*	-0.0048	-0.0275	-0.0081	-0.0045	-0.0047
	(1.58)	(-0.37)	(-0.60)	(-0.52)	(-0.53)	(-0.70)
$lnTA$	0.0020	0.0011	-0.0014	-0.0027**	-0.0016**	-0.0039**
	(0.44)	(0.18)	(-0.39)	(-2.28)	(-2.48)	(-2.71)
Year fixed	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES
Observations	3878	3878	3878	3878	3878	3878
R-squared	0.8849	0.8783	0.8697	0.4692	0.4728	0.4769

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

4.2.2 The Mediating Effects of Air Pollution

To shed further light on the effect of the HSR on the climate, we consider air pollution as a mediator in the relationship between climate change and the HSR opening. CO2, SO2, and PM2.5 measure air pollution. As previously, we employ the three-step approach. The estimated first-step regression model was summarised in columns 1-3 of Table 4. We regress the hypothesised mediators on the HSR opening in the second step. Table 5 displays the results, which indicate that the opening of HSR significantly reduces CO_2, SO_2, and $PM_{2.5}$.

Table 5. Impact of HSR Opening on Air Pollution

Independent Variables	Mediating Variables		
	$lnCO_2$	$lnSO_2$	$lnPM_{2.5}$
	(1)	(2)	(3)
$TREAT \times AFTER$	-0.0329***	-0.1441***	-0.0671**
	(-5.19)	(-3.46)	(-2.72)
$lnUS$	0.0059	0.0153	-0.0229***
	(0.59)	(0.85)	(-5.29)
$lnGI$	0.1349***	0.1389**	-0.0265
	(5.98)	(2.77)	(-0.59)
$lnGDP$	0.1277***	-0.0056	-0.0029
	(5.76)	(-0.10)	(-0.49)
$lnES$	0.0168	-0.0170	0.0019
	(0.61)	(-0.58)	(0.75)
$lnTA$	0.0176***	-0.0145	-0.0137***
	(4.29)	(-0.29)	(-5.96)

Year fixed	YES	YES	YES
City fixed	YES	YES	YES
Observations	3878	3878	3878
R-squared	0.8918	0.9083	0.8879

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

In the third step, we consider both the HSR and the mediators as drivers of climate change. The coefficient estimates of the HSR opening on the climate conditions are lower in absolute value in the third-step regression (-0.0073 and 0.0068 in columns 2 and 4 of Table 6, respectively) than in the first-step regression (-0.0112 and 0.0121 in columns 1 and 3 of Table 4, respectively). Therefore, air pollutants appear to mediate the relationship between the HSR opening and the climatic conditions.

Table 6. Impact of HSR Opening on Climate Change

Independent Variables	Dependent Variables	
	$lnTEMP$	$lnSUN$
	(1)	(2)
$TREAT \times AFTER$	-0.0073***	0.0068***
	(-3.78)	(5.31)
$lnCO_2$	0.0087***	-0.0075***
	(4.56)	(-4.40)
$lnSO_2$	0.0067***	-0.0093
	(4.27)	(-0.46)
$lnPM_{2.5}$	0.0039***	-0.0047***
	(4.21)	(-4.67)
$LnUS$	0.0412***	0.0058
	(2.95)	(0.76)
$LnGI$	-0.0054	-0.0161***
	(-0.71)	(-3.77)
$LnGDP$	-0.0018	0.0167**
	(-0.70)	(2.58)
$LnES$	0.0121**	-0.0086
	(2.35)	(-0.59)
$LnTA$	0.0034	-0.0052
	(0.11)	(-0.36)
Year fixed	YES	YES
City fixed	YES	YES
Observations	3878	3878
R-squared	0.8896	0.8927

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

Considering Tables 5 and 6 together, we find that the HSR opening inhibits CO_2, SO_2, and $PM_{2.5}$ emissions, which reduces urban temperature and increases sunshine duration. The HSR can help to reduce SO_2 emissions by improving production efficiency and resource utilisation, and changing the industrial structure (Chen et al., 2020). Overall, the results are supportive of Hypothesis 3.

4.2.3 The Mediating Effects of Factor Agglomeration

We now consider factor agglomeration mediating between climatic conditions and urban GTFP. Temperature and sunshine duration affect urban GTFP through talent gathering ($lnTG$), investment gathering ($lnIG$), and green technology concentration ($lnGT$). We proceed in three steps. In the first step, we regress GTFP on temperature (column 1 of Table 7). In this step, temperature appears to cause a negative effect on GTFP In the second step; temperature commands a significant decline in factor agglomeration (see columns 2-4). In the third step, GTFP is regressed on both urban temperature and factor agglomeration (column 5). All in all, factor agglomeration triggers significant mediating effects between temperature and GTFP. Table 7 indicates that temperature decreases urban GTFP by inhibiting factor agglomeration. Overall, our findings support Hypothesis 4.

Table 7. The Mediating Effects of Factor Agglomeration: Urban Temperature

Independent Variables	Mediating/Dependent Variables				
	$lnGTFP$	$lnTG$	$lnIG$	$lnGT$	$lnGTFP$
	(1)	(2)	(3)	(4)	(5)
$lnTEMP$	-0.0066*	-0.0015**	-0.0012*	-0.0018*	-0.0043
	(-1.72)	(-2.23)	(-1.71)	(-1.66)	(-0.53)
$lnTG$					0.0061**
					(2.03)
$lnIG$					0.0031**
					(2.22)
$lnGT$					0.0036**
					(2.18)
$lnUS$	0.0016	0.0571***	-0.0813***	0.2356***	-0.0065
	(0.53)	(8.88)	(-3.70)	(6.14)	(-1.53)
$lnGI$	-0.0095***	0.0102	0.0580***	0.1215**	-0.0022
	(-3.30)	(0.88)	(6.05)	(2.02)	(-0.78)

$lnGDP$	0.0061*	-0.0520**	0.0383***	0.0557	0.0098**
	(1.66)	(-2.03)	(3.35)	(0.70)	(2.13)
$lnES$	-0.0016	0.0098	-0.0325*	0.0642	-0.0062*
	(-0.66)	(0.72)	(-1.66)	(1.20)	(-1.87)
$lnTA$	-0.0019**	-0.0006	0.0127	0.0579***	-0.0016*
	(-2.23)	(-0.13)	(1.33)	(7.09)	(-1.75)
Year fixed	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES
Observations	3878	3878	3878	3878	3878
R-squared	0.5846	0.6531	0.6432	0.6231	0.6287

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis

Further, we replace temperature with sunshine duration and undertake the three-step approach. Table 8 summarises the estimated regressions. Factor agglomeration appears to mediate the relationship between climatic conditions and GFTP. The results summarised in Tables 7 and 8 lend support to Hypothesis 4. Factor agglomeration can accelerate environmental innovation and increase energy efficiency, which is conducive to lower pollution emissions through green knowledge, environmental protection resource sharing, and equivalent effects (Shen & Peng, 2021).

Table 8. The Mediating Effects of Factor Agglomeration: Sunshine Duration

Independent Variables	Mediating/Dependent Variables				
	$lnGTFP$	$lnTG$	$lnIG$	$lnGT$	$lnGTFP$
	(1)	(2)	(3)	(4)	(5)
$lnTEMP$	0.0076***	0.0205**	0.0074*	0.0012*	0.0058***
	(2.99)	(2.06)	(1.72)	(1.67)	(2.84)
$lnTG$					0.0112**
					(2.25)
$lnIG$					0.0118***
					(5.10)
$lnGT$					0.0003**
					(2.11)
$lnUS$	0.0014	0.0554***	-0.0802***	0.0241***	-0.0065
	(0.46)	(18.90)	(-3.69)	(6.29)	(-1.53)
$lnGI$	-0.0089***	0.0111	0.0581***	0.0117*	-0.0018
	(-3.10)	(0.95)	(4.41)	(1.95)	(-0.62)
$lnGDP$	0.0058	-0.0523***	-0.0289*	0.0589	0.0095**
	(1.58)	(-4.08)	(-1.67)	(0.73)	(2.04)

$lnES$	-0.0016 (-0.64)	0.0103 (0.74)	0.0128 (1.54)	0.0685 (1.29)	-0.0063* (-1.87)
$lnTA$	-0.0018** (-2.17)	-0.0004 (-0.08)	0.0114* (1.67)	0.0578** (2.11)	-0.0016* (-1.72)
Year fixed	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES
Observations	3878	3878	3878	3878	3878
R-squared	0.5860	0.5746	0.5947	0.5832	0.5542

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

4.3 Robustness Checks

To analyse the robustness of our research findings, the HSR opening dummy was replaced with two alternative measures of HSR network, the city's network connection breadth and network centrality, DC, and CC, respectively.

In the first step, we regress GTFP on the HSR network. The first-step regression is summarised in Table 9. The coefficient estimates of the HSR network are positive and significant. It indicates that HSR has a significant impact on GTFP in prefecture-level cities.

Table 9. Impact of HSR Network on Urban GTFP

Independent Variables	Dependent Variable: $lnGTFP$	
	(1)	(2)
$TREAT \times AFTER \times DC$	0.0073*** (5.73)	
$TTREAT \times AFTER \times CC$		0.0027*** (3.35)
$lnUS$	-0.0003 (-0.11)	0.0008 (0.26)
$lnGI$	-0.0089*** (-3.06)	-0.0096*** (-3.29)
$lnGDP$	0.0081** (2.08)	0.0072* (1.90)
$lnES$	-0.0017 (-0.70)	-0.0014 (-0.59)
$lnTA$	-0.0018** (-2.18)	-0.0018** (-2.18)
Year fixed	YES	YES
City fixed	YES	YES
Observations	3878	3878

R-squared	0.5905	0.5862

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

In the second step, we regress the climatic conditions (temperature and sunshine duration) on the HSR network. The results are displayed in columns 1 and 2 of Tables 10 and 11 for the DC and CC measures of the HSR network, respectively. We find that the HSR network significantly affects the climatic conditions (temperature and sunshine duration). In particular, the HSR network is negatively associated with temperature and positively with sunshine duration.

In the third step, GTFP appears to respond significantly to climatic conditions. The temperature has a negative effect, whereas sunshine duration positively affects GTFP. The effect of the HSR network appears to decrease in the third-step regression (0.0049 and 0.0053, if temperature and sunshine duration are included in the regression, respectively) relative to the first-step regression (0.0073). This result indicates that the climatic conditions partially mediate the effects of the HSR network on GTFP.

Table 10. Impact of HSR Network (DC) on Urban GTFP

Independent Variables	Dependent Variables			
	$lnTEMP$	$lnSUN$	$lnGTFP$	
	（1）	（2）	（3）	（4）
$TREAT \times AFTER \times DC$	-0.0093***	0.0104**	0.0049***	0.0053***
	（-3.69）	（2.29）	（6.11）	（3.38）
$lnTEMP$			-0.0035**	
			（-2.57）	
$lnSUN$				0.0069***
				（6.36）
$lnUS$	0.0163**	0.0073	-0.0059	-0.0027
	（2.56）	（0.78）	（-0.34）	（-0.48）
$lnGI$	0.0010	-0.0405***	-0.0038***	-0.0058***
	（0.14）	（-3.29）	（-4.49）	（-4.79）
$lnGDP$	0.0028	0.0167	0.0116***	0.0054**
	（0.39）	（1.52）	（3.89）	（2.39）
$lnES$	0.0192*	-0.0107	-0.0058	-0.0016
	（1.84）	（-1.10）	（-0.49）	（-0.56）
$lnTA$	0.0019	-0.0054	-0.0046**	-0.0066**
	（0.53）	（-1.47）	（-2.21）	（-2.03）

Year fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	3878	3878	3878	3878
R-squared	0.9825	0.9030	0.5798	0.5872

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

Table 11 summarises the second- and third-step regressions for the CC measure of the HSR network. Consistently with the results reported in Table 10, the second-step regression shows that the HSR network is negatively (positively) associated with temperature (sunshine duration). The third-step regression seeks to evaluate the effect of the HSR network controlling for the mediators. We find that the effect of the HSR network is positive and significant (0.0019 and 0.0008, if temperature and sunshine duration are included in the regression, respectively), and somewhat smaller than in the first-step regression (0.0027). Again, there is evidence that the climatic conditions partially mediate the relation between the HSR network and GTFP.

The robustness analysis endorses our key findings. Overall, the results summarised in Tables 9-11 support the mediating role of temperature and sunshine duration.

Table 11. The Impact of HSR Network (CC) on Urban GTFP

	$lnTEMP$	$lnSUN$	$lnGTFP$	
	(1)	(2)	(3)	(4)
$TREAT \times AFTER \times CC$	-0.0075***	0.0130**	0.0019***	0.0008***
	(-3.60)	(2.33)	(4.93)	(5.38)
$lnTEMP$			-0.0013***	
			(-3.81)	
$lnSUN$				0.0087***
				(5.39)
$lnUS$	0.0161**	0.0104	0.0011	0.0015
	(2.51)	(1.13)	(0.39)	(0.29)
$lnGI$	0.0020	-0.0414***	-0.0048***	-0.0034***
	(0.28)	(-3.31)	(-4.12)	(-3.46)
$lnGDP$	0.0022	0.0130	0.0042**	0.0019**
	(0.32)	(1.15)	(2.02)	(2.38)
$lnES$	0.0185*	-0.0109	-0.0043	-0.0051
	(1.78)	(-1.11)	(-0.42)	(-0.68)
$lnTA$	0.0018	-0.0055	-0.0058***	-0.0069**
	(0.50)	(-1.50)	(-3.69)	(-2.13)

Year fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	3878	3878	3878	3878
R-squared	0.9825	0.9028	0.5663	0.5761

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. We report t statistics in parenthesis.

5. Conclusion and Implications

Understanding the association between the opening of the HSR and urban GTFP is critical for evaluating how innovative rail infrastructure influences green innovation development in China. This study employs panel data from 277 prefecture-level cities in China between 2003 and 2016 and a two-way fixed-effects model to assess the impact of the HSR opening on urban GTFP.

Our results indicate that the introduction of HSR services significantly boosts urban GTFP. We also provide evidence that the effect of the HSR opening on GTFP significantly varies across regions and urban grades. Moreover, we used the three-step approach to evaluate the mediating role of changing climatic conditions (temperature and sunshine duration) in the relationship between the HSR and GTFP. The HSR network expansion inhibits urban temperature and promotes sunshine duration by reducing air pollution. We also find that factor agglomeration is a vector of significant mediators in the relationship between the climatic conditions (temperature and sunshine duration) and GTFP.

Our findings offer several policy implications. Firstly, greater investment in innovative and modern transportation infrastructure in prefecture-level cities accelerates the process of regional integration. The HSR network expansion gives rise to economic benefits for urban and regional economies, highlighting innovative transportation infrastructure's critical role in promoting GTFP. Secondly, stable environmental conditions and the advancement in production factors are instrumental in improving GTFP. Specifically, by reducing input redundancy in production processes, the Chinese government can attain lower air pollution levels (in terms of (CO_2, SO_2, and PM2.5 emissions) and ensure stable climatic conditions, which ultimately improves GTFP. Crucially, the HSR opening can translate into both economic and environmental benefits. In fact, our research demonstrates that innovative infrastructure projects create no tension between two arguably conflicting goals, economic and environmental performance. Investors, highly skilled labour, and innovators are attracted by the improved connectivity of cities and regions, lower pollution levels, and improved climatic conditions, which stimulate GTFP. Therefore, it is imperative to factor in the full range of economic, environmental, and social benefits when appraising innovative infrastructure projects. The Chinese government can also undertake public infrastructure projects to secure green and sustainable growth as a macroeconomic policy instrument. Also, promoting factor agglomeration through improved rail connectivity can help to alleviate social tensions that might arise due to intra -and inter-regional income disparities.

Our study has a few limitations. We focus on the impact of the HSR opening on GTFP in prefecture-level cities by taking a macro perspective. This perspective overlooks internal channels and micro-foundations. Whether the opening of the HSR commands a change in business opportunities and an increase in entrepreneurial activity in prefecture-level cities can provide a promising avenue for future research using micro-level data and expanding the sample size. Further, this research does not necessarily account for the full range of mediators for the HSR-GTFP relationship. Therefore, future research could expand the vector of mediating variables.

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Appendix

Table A1. Data Sources and Description of Variables

Variable Name	Measurement	Source
Green total factor productivity (GTFP)	Global Malmquist-Luenberger Index approach to evaluate the green total factor productivity at the city level	China City Statistical Yearbook
The opening of high-speed rail (TREAT × AFTER)	The value is 1 if the HSR is opened in city i in the t year; otherwise, it is 0.	Railway Corporation and news reports / National Railway Administration announcements
Urban size (US)	Total urban employed population at the end of the year	China City Statistical Yearbook
Government intervention (GI)	General budget expenditure of prefecture-level city government	China City Statistical Yearbook
Urban economic development level (GDP)	Per capita GDP of prefecture-level cities	China City Statistical Yearbook
Urban economic structure (ES)	Proportion of prefecture-level city tertiary industry	China City Statistical Yearbook
Technological advance (TA)	Number of patents granted by prefecture-level cities	China City Statistical Yearbook
Carbon emission (CO2)	Total urban carbon dioxide emissions	China City Statistical Yearbook / China Bureau of Statistics
Sulphur dioxide emission (SO2)	Total urban sulphur dioxide emissions	China City Statistical Yearbook
Haze pollution (PM2.5)	Annual mean value of PM2.5 in prefecture-level cities	Dalhousie University in Canada, Atmospheric Composition Analysis Group
Urban Temperature (TEMP)	Annual mean temperature of prefecture-level cities	Meteorological station data within the jurisdiction of prefecture-level cities
Urban sunshine hours (SUN)	Annual sunshine hours in prefecture-level cities	Meteorological station data within the jurisdiction of prefecture-level cities
Talent gathering (TG)	Agglomeration location entropy of R&D personnel (full-time equivalent) in high-tech industries	China City Statistical Yearbook
Investment gathering (IG)	Proportion of urban foreign direct investment in national foreign direct investment	China City Statistical Yearbook
Green technology concentration (GT)	Proportion of urban green patent applications to national green patent applications	Patent Database of State Intellectual Property Office of China