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Original Research

The Impact of High-Speed Rail on Regional Green Innovation Performance-Based on the Dual Perspective of High-Speed Rail Opening and High-Speed Rail Network

Yanfei Zhou*, Qi Fan, Chunliu Tao

Suzhou Chien-Shiung Institute of Technology, Taicang Jiangsu 215411,
No. 1, Jianxiong Road, Science and Education New City, Taicang Jiangsu, China

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Abstract

Based on the panel data of 108 cities in the Yangtze River Economic Belt from 2009 to 2019, this study combines the difference-in-differences (DID) method with the mediation effect model to examine the impact of the opening of high-speed rail (HSR) on regional green innovation performance. It is found that the opening of HSR has significantly improved the regional green innovation performance, and this boosting effect shows an increasing trend over the years. In addition, the impact of the opening of HSR on regional green innovation performance varies significantly depending on geographic location and city size. Further, the measurement of the centrality of the HSR network employing social network analysis (SNA) indicates that the communication ability of node cities' transportation pulse is increasing, and the connection breadth of the HSR network has a positive impact on the regional green innovation performance. The findings supplement the current economic and environmental effects of HSR and provide a new idea and direction for understanding the relationship between HSR and regional green innovation and optimizing the layout of the HSR networks.

Keywords: HSR, green innovation performance, DID, SNA, mediation effect

Introduction

In the context of the large-scale development of China's railroads, the construction of HSR has not only improved people's travel mode, but also had a profound impact on regional economic development, factor flow and industrial structure. In addition, HSR, as a kind of green transportation, is the practical manifestation of green and sustainable development policy in transportation construction. By the end of 2021, China's HSR had reached 40,000 km of operating mileage, ranking first in the world, and a modern HSR network has been shaped [1]. According to the Medium- and Long-term Railway Network Planning (2016-2030), China aims to build a blueprint for HSR network with "eight vertical and eight horizontal" as the main trunk,

*e-mail: zyfyibuduo@126.com

supplemented by intercity railroads [2]. At the same time, the drawbacks of the traditional sloppy economic growth model have also begun to be highlighted. With an aim to alleviate the increasingly serious environmental pollution problem and promote green development from "campaigning" to "institutionalization", the Chinese government has successively issued a series of documents such as "Several Opinions on Delineating and Strictly Adhering to the Ecological Protection Red Line" [3]. During the "14th Five-Year Plan" period, China's economy has entered a new normal, with major energy consumption peaking successively. Green development will be transformed from an external burden to a competitive advantage, becoming the key to improving economic benefits. With the spread of the COVID-19 pandemic and the intensification of the Sino-US game, the uncertainty of the external environment facing China's development has aggravated, and the previous "externally-oriented" economic growth mode is difficult to maintain [4]. The Chinese government has proposed to establish a "dual circulation" development pattern in which the domestic economic cycle plays a leading role. Thus, whether to improve the domestic transportation infrastructure as a breakthrough to promote regional green development has become the focus of sustainable economic development.

The remainder of the study is structured as follows. Section 2 presents the literature review. Section 3 explains the theoretical analysis and research hypothesis. Section 4 provides the methodology and data. Section 5 interprets empirical results and discussion. The final section concludes with the main findings and policy implications.

Literature Review

The Growth Effect of HSR

At present, the effects of HSR on regional economic development [5-7], regional spatial structure [8-9] and population mobility [10-11] have become hot issues. However, the analysis of the growth effect caused by HSR is often limited to a single perspective, that is, the economic effect and the environmental effect are separated from each other. Among them, scholars mainly hold two views on the role of economic growth, one believes that HSR promotes economic growth [12-13] and the other believes that HSR promotes economic growth while suppressing economic growth in less developed regions [14-15].

HSR & Environment

Research on the environment can be broadly divided into three areas: (1) Studies based on the life-cycle approach (PCA). For example, Chester and Horvath conducted an environmental life cycle assessment of four modes of transportation: HSR, automobile, light rail, and airplane [16]. Akerman analyzed the Swedish HSR track Europabanan from a life cycle perspective [17]. (2) The environmental impact of HSR compared with other modes of transportation. For instance, D'Alfonso et al. compared the environmental impact of air transport and HSR competition [18]. Givoni assessed the impact of flights and HSR between London and Paris on local air pollution (LAP) and climate change [19]. (3) The effect of HSR on environmental pollution. Most scholars concluded that the opening of HSR has a significant pollution reduction effect, e.g., D'Alfonso et al. demonstrated that the introduction of HSR reduced greenhouse gas emissions although it increased LAP [20]. Yang et al. found that the pollution reduction effect of HSR was more significant in cities with larger cities, higher economic levels, more abundant human capital or stricter environmental regulation [21].

HSR & Innovation

In addition, compared with traditional transportation modes, HSR not only enhances inter-regional geographical accessibility, but also has the advantages of high passenger capacity, speed, punctuality, and safety, which can better meet the demand for time-sensitive and highly qualified talents. Besides, the opening of HSR reduces the cost of mobility, increases the speed and scale of mobility, and accelerates the dissemination of knowledge between regions, thus promoting knowledge spillover, technological progress, and new knowledge creation [22-23], and further having a profound impact on regional innovation activities [24]. Regarding the research on HSR and regional innovation, some scholars have explored the knowledge and technology flow triggered by the opening of HSR from the perspective of knowledge spillover, e.g., Chen and Hall argued that HSR compresses spatial and temporal distances and facilitates knowledge generation [25]. Since then, Chen further found that HSR can promote knowledge and technology flow and trigger knowledge spillover [26]. Furthermore, HSR promotes the dissemination of knowledge and other "soft information" and innovation activities [27], and its innovation effect on cities is inversely proportional to the distance from the central city [28]. Based on regional innovation, some scholars have explored the mechanism and heterogeneity of the effect of HSR on green total factor productivity [29-30].

SNA & DC

Social Network Analysis (SNA) is a quantitative tool that integrates mathematical and computational applications to analyze the intricate interdependencies between various elements and to understand the characteristics and meaning of the structure of these relationships [31]. Numerous studies have explored the spatial network of regional urban agglomerations using SNA, e.g., Han et al. analyzed the network characteristics of changes in spatial economic connections in the Wanjiang urban belt based on the SNA [32]. Fang and Sun used SNA to analyze the evolution of spatial structure characteristics of the Yangtze River Delta urban agglomeration before and after the HSR era [33]. Yang and Liu explored the impact of spatially linked network structure on low-carbon innovation by employing SNA [34].

"Centrality" is the focus of SNA, and what kind of power members have in their social networks was one of the first elements explored by social network analysts, who defined power quantitatively from a relational perspective and measured it through a centrality index [35]. Centrality is a measure of the degree to which a member is at the center of the network, with degree centrality (DC) being the most commonly used, obtained by counting how many points it is directly connected to, with large values indicating that the member is at the center.

In summary, most of the existing studies divide the economic and environmental effects of HSR, partly extending to the impact of HSR on regional innovation and partly exploring the impact of HSR on regional green total factor productivity. Most of the studies only focus on the "opening of HSR", ignoring the regional impact of the HSR network as a whole. Actually, HSR promotes the rational layout of innovation factors across regions, enhances knowledge spillover effects, and realizes resource Pareto optimization, which is of great significance to regional green innovation development. Green innovation aims to reduce resource consumption, diminish environmental pollution, help enterprises improve output efficiency and increase economic and environmental benefits, and is a key catalyst for sustainable development by combining innovation with the environment [36]. Given this, this paper innovatively explores the impact of HSR opening on regional green innovation performance from the perspective of factor flow in order to better promote regional green development.

Compared with previous literature, the marginal contributions of this paper are as follows: firstly, the research focuses on the impact of HSR on regional green innovation performance, which is analyzed from the dual perspectives of HSR opening and HSR network. Secondly, the research strategy combines DID method and mediating effect model to analyze the impact mechanism of HSR opening on regional green innovation performance from the perspective of factor flow. Thirdly, in terms of research methods, on the one hand, this study adopts a three-stage DEA-Malmquist method to measure the efficiency of regional green innovation in order to eliminate the interference of environmental factors and random errors, and integrates efficiency indicators to make a comprehensive evaluation of green innovation performance. On the other hand, taking the opening of HSR as a "quasi-natural experiment", the PSM-DID model is applied to empirically examine the effect of the opening of HSR on regional green innovation performance. Moreover, this paper further extends to detect the impact of the HSR network on regional green performance combined with SNA.

Theoretical Analysis and Research Hypothesis

Mechanisms Analysis and Baseline Hypothesis

Compared to traditional transportation, HSR has the dual advantage of high speed and high operating density. It was found that the number of patents of companies along the HSR lines increased significantly after the HSR opening [37], which contributed to promoting innovation investment by local companies [38]. In addition, PM2.5 concentrations in cities with HSR openings were 1.81% lower than those in cities without openings [39]. HSR can promote green technology innovation in enterprises and suppress SO_2 emissions [40], while the optimization of HSR network also has a positive effect on urban eco-efficiency [41]. Thus, on the one hand, the opening of HSR shortens the spatial and temporal distance between cities, accelerates the cross-regional flow of innovation factors, provides opportunities for inter-regional exchanges and cooperation, and enhances the technological innovation level and productivity of lagging enterprises. On the other hand, the technological innovation brought by HSR is conducive to reducing pollution emissions and achieving green development.

Therefore, this study intends to explore the mechanism of the impact of HSR opening on regional green innovation performance from the perspective of innovation factor flow. Firstly, HSR can better meet the demand for time-sensitive and highly qualified talents, and the cross-regional flow of innovation factors improves the availability of advanced green technologies in backward regions. Innovation factor input is a critical link to guarantee green innovation activities and improve green innovation output. However, the initial distribution of resources required for green innovation is often uneven due to geographical constraints. The "time-space compression effect" generated by HSR promotes the initial distribution and redistribution of these resources in different regions, optimizes the spatial distribution of innovation factors, and enhances the green innovation potential of regions.

Secondly, the opening of HSR promotes inter-regional knowledge spillover. Compared with traditional factors, high-quality talents carried by HSR are knowledge and technology-intensive, and the flow of innovation factors is conducive to optimizing the knowledge flow structure, enhancing the inter-regional knowledge linkage [42] and knowledge spillover effect [43], further promoting the "imitation effect", "learning effect" and "exchange effect", thus enabling advanced green production concepts and green innovation technologies to be applied more quickly in a larger spatial scope, assisting enterprises to understand consumer demand more accurately and timely, reducing production losses and resource wastage, and ultimately promoting the improvement of regional green innovation performance.

Thirdly, the HSR provides a channel for communication between regional green innovation subjects, which greatly promotes the formation of green innovation networks among different cities, effectively improves the cooperation and communication among researchers, and the concept of green technology innovation is continuously disseminated and condensed. With the continuous enhancement of inter-regional green innovation links, externalities emerge, and the positive externalities of the green innovation network further promote the green innovation performance of the whole region.

Thus, on the basis of the aforementioned analysis, the first hypothesis is set out as follows:

Hypothesis 1a. The opening of HSR has a catalytic effect on regional green innovation performance enhancement.

Hypothesis 1b. The flow of innovation factors is the critical path for the opening of HSR to promote regional green innovation performance enhancement.

Expanded Research Hypothesis

Hypothesis for Two Types of Heterogeneous Sub-Samples

Since the economic characteristics and geographical locations of different regions have different impacts of HSR opening on total factor productivity in each region [44], the impacts of HSR on green innovation performance in different geographic locations are differentiated. In addition, the impact of HSR on the regional economy shows a city-level structural distribution [45]. Therefore, the impact of HSR on its green innovation performance may also differ for cities of different levels. Based on the above analysis, two additional hypotheses are proposed.

Hypothesis 2. For different geographic locations, the impacts of HSR on green innovation performance are heterogeneous.

Hypothesis 3. For different city sizes, the impacts of HSR on green innovation performance are heterogeneous.

Hypothesis for Dynamic Effect

In the early period when the HSR was first opened, there was little exchange and cooperation, and the impact of the HSR on regional green innovation performance might not be obvious. However, as the elapse of time, people's preference for HSR increased and the comparative advantages of HSR over other transportation modes gradually came to the fore, leading to wider inter-regional exchanges and more frequent cooperation, and the impact of HSR on regional green innovation performance became increasingly evident. Accordingly, the following hypothesis is proposed.

Hypothesis 4. The impact of HSR on regional green innovation performance has a dynamic characteristic.

Methodology and Data

Empirical Model

Baseline Model

Difference-in-differences (DID), as a classical method for policy effect evaluation, not only circumvents the endogeneity problem, but also accurately estimates the policy effect. According to the collated data, as of the end of 2019, 91 of the 108 cities in the Yangtze River Economic Belt have been opened by HSR and 17 have not been opened, which provides a good "quasi-natural experiment" for DID. Therefore, the 91 opened cities are used as the "treatment group" and the remaining 17 cities are used as the "control group" to test the impact of HSR opening on regional green innovation performance using DID. Since the opening time of HSR is not uniform across cities, the cities in the treatment group are assigned a value of 1, the cities in the control group are assigned a value of 0, the year of opening and later are assigned a value of 1, and the time before opening is assigned a value of 0. The dummy variable *HSR* is generated instead of the interaction term *treat*×*time* and is used as the core explanatory variable. Since the model already controls for individual and time effects, to avoid multicollinearity, only the interaction term *HSR* is retained, and *treat* and *time* are omitted. The model is constructed as follows.

$$\ln GE_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

where i represents the city, t represents the year. GE_{it} is the explanatory variable, indicating the green innovation performance of city i in year t. HSR_{it} is the core explanatory variable, which denotes whether HSR opening in city i in year t, i.e., if the HSR is opened, it takes the value of 1 and 0 otherwise. X_{it} is the control variable. μ_i and δ_t are individual fixed effects and time fixed effects, respectively. ε_{it} is the random error term.

In addition, to examine the dynamic effect of HSR opening on regional green innovation performance, the dummy variables $YEAR_j$ for 5 years before and 5 years after HSR opening were set [46], and multiplied by the dummy variable *HSR* as the core explanatory variable. The model is shown in Eq. (2).

$$\ln GE_{it} = \beta_0 + \sum_{j=1}^{5} \beta_j (HSR_{it} \times YEAR_j) + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

where $YEAR_j$ is the dummy variable, set the *jth* year before the opening of the HSR to 0, and the *jth* year after the opening of the HSR to 1, $j \in [-5,5]$. The rest of the variables have the same meaning as Eq. (1).

Mechanism Test Model

Theoretical analysis shows that the opening of HSR has a catalytic effect on the improvement of regional green innovation performance, so how does the opening of HSR affect green innovation performance? As the theoretical analysis above, HSR may affect knowledge spillover through factor flow, which in turn affects regional innovation and ecological environment, and ultimately promotes the improvement of green innovation performance. To verify the hypothesis, the model is set up according to the three-step test of mediating effect as follows.

$$\ln GE_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{3}$$

$$PFL_{it} = \lambda_0 + \lambda_1 HSR_{it} + \varphi X_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{4}$$

$$\ln GE_{it} = \phi_0 + \phi_1 HSR_{it} + \theta PFL_{it} + \eta X_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{5}$$

where *PEL* denotes the mediating variable and the other variables are set as above. Eq. (3) is to re-examine the relationship between GE and HSR. Eq. (4) is a check of the relationship between the mediating variable innovation factor flow and HSR. Eq. (5) is to verify the relationship between GE and HSR when controlling for the mediating variables in the regression model.

Variable Selection

Explained Variables

Given that this dissertation focuses on exploring the impact of HSR opening on regional green innovation performance, the green innovation performance of 108 cities in the Yangtze River Economic Belt is selected as the explanatory variable. Among which, the green innovation efficiency is calculated by the three-stage DEA-Malmquist method [47], and on this basis, the green innovation performance is further obtained by incorporating efficiency indicators by using the entropy weight method.

Other Explanatory Variables

(1) Core explanatory variables

The core independent variable is the dummy variable *HSR*. It should be noted that, first, for cities with multiple HSRs, the earliest year is used as the time when the city opens the HSR. Second, given that the opening of HSR in some cities is at the end of the year, the knowledge spillover effect and its impact on regional green innovation may not be apparent in a short period. Hence, the opening time of HSR in these cities is treated with a lag of one year.

(2) Control variables

The five control variables are selected to ensure the stability of the estimated results [29]; Zhang and Feng [39], i.e., industrial structure (*IS*), government intervention (*GOV*), human capital (*HUM*), technological progress (*TEC*) and foreign direct investment (*FDI*). They were introduced and measured by the share of the added value of the tertiary industry in GDP, general public budget expenditure, number of university students, number of patents granted and actual utilization of FDI in each city, respectively.

(3) Mediating variables

Given that HSR serves time-sensitive senior talents, the HSR network mainly promotes regional green innovation through the movement of people rather than capital [48]. Therefore, the innovation factor flow mainly considers the movement of people, specifically measured by the amount of R&D personnel flow, which is calculated as follows.

$$PFL_{ij} = \ln M_i * \ln(Wage_j - Wage_i) * R_{ij}^{-2} \tag{6}$$

where M_i is the number of R&D personnel in city *i*; $Wage_j$ and $Wage_i$ are the average wages of employed persons in urban units in provincial capital city *j* and city *i*, respectively, and R_{ij} is the distance between the two cities.

Construction of HSR Network

The specific steps are as follows: (1) Define the city node *N*. (2) If an HSR line *R* is opened between two cities, the two cities are connected by a connection line *L*. (3) The HSR network is noted as *G* = (*N, L, R*). Before employing the SNA to establish the network structure, a 108*108 matrix is constructed. Then the relationship matrix is transformed into a *0-1* matrix, and if the HSR between two cities can be directly connected, the matrix element takes the value of 1, which indicates that there is a relationship between the two regions, and vice versa takes 0, which means there is no significant association, and the diagonal element is set to 0. The influence of cities in the HSR network is examined by constructing DC, the higher the DC value, the more extensive the HSR network connection [49]. The DC is calculated as in Eq. (7).

$$DC_{it} = {k_{it}} / {N-1} \tag{7}$$

where DC_{it} denotes the degree centrality of city *i* in period *t*, k_{it} is the number of cities directly connected to city *i* in period *t*, and *N*–1 is the maximum degree value of the node.

Table 1. The descriptive statistics.

Variables	Sample size	Mean	Std.dev	Min	Max	Unit
GE	1188	0.39	0.12	0.17	1.15	-
PFL	1188	39.97	9.37	20.66	77.49	-
IS	1188	4260235.14	6859232.49	356712.00	83515363.00	%
GOV	1188	101279.56	177641.82	231.00	1006894.00	Million (CNY)
HUM	1188	6397.24	12367.00	12.00	100020.00	Person
TEC	1188	113063.66	230730.40	3.00	1904791.00	-
FDI	1188	0.39	0.12	0.17	1.15	Million(dollar)

Data

The sample data in this paper are the balanced panel data of 108 cities in the Yangtze River Economic Belt from 2009 to 2019. The data mainly come from http://www.china-railway.com.cn, https://www.12306.cn, https://navi.cnki.net/knavi/yearbooks/YZGCA/detail and http://www.stats.gov.cn/tjsj/ndsj. The missing data are filled by calculating the average growth rate, and the results of descriptive statistics of variables are shown in Table 1.

Results and Discussion

Parallel Trend Hypothesis

The condition for using DID is to satisfy the parallel trend assumption, i.e., there is no systematic difference in the green innovation performance of cities before and after the opening of HSR regardless of whether they open HSR, which is demonstrated here by plotting the temporal trend of the explanatory variables. For the selection of time nodes, by observing the number of cities in the Yangtze River Economic Belt that opened HSR in all years [24]. It is found that the years of HSR opening were mainly concentrated in 2014 and 2019, and 2014 was selected as the time node due to the large span between years and the small sample data around 2019. Besides, observing the parallel trend graph of green innovation performance of cities with and without HSR opening (Fig. 2), it is found that the trend of green innovation performance of cities with and without HSR opening before 2014 is the same. Thus, the hypothesis of parallel trend is verified and the DID model is applicable.

Baseline Regression

To detect the impact of HSR opening on regional green innovation performance, DID was used to examine the results as shown in Table 2. Columns (1) and (2) reflect the impact of HSR opening on regional green innovation performance, and the comparison

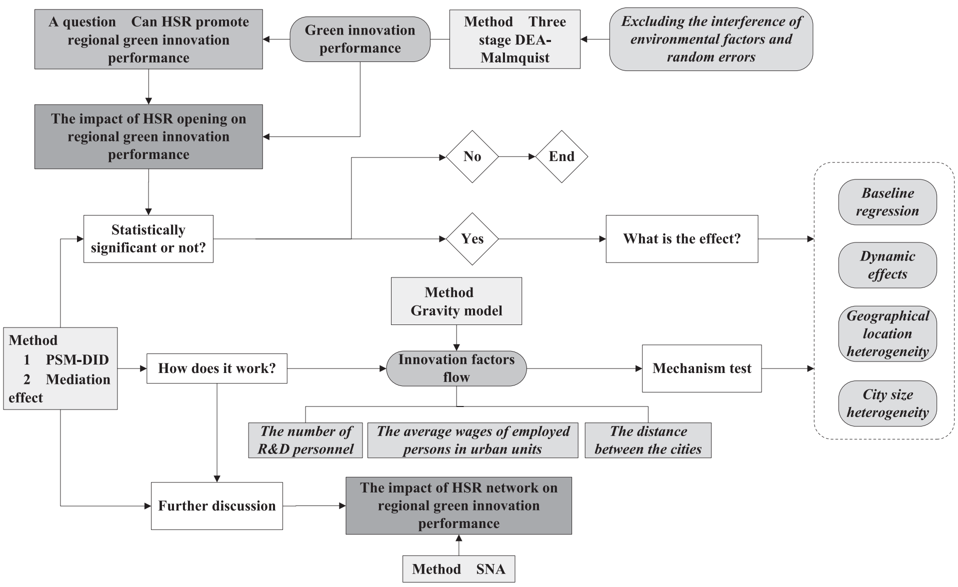

Fig. 1. Flowchart of framework.

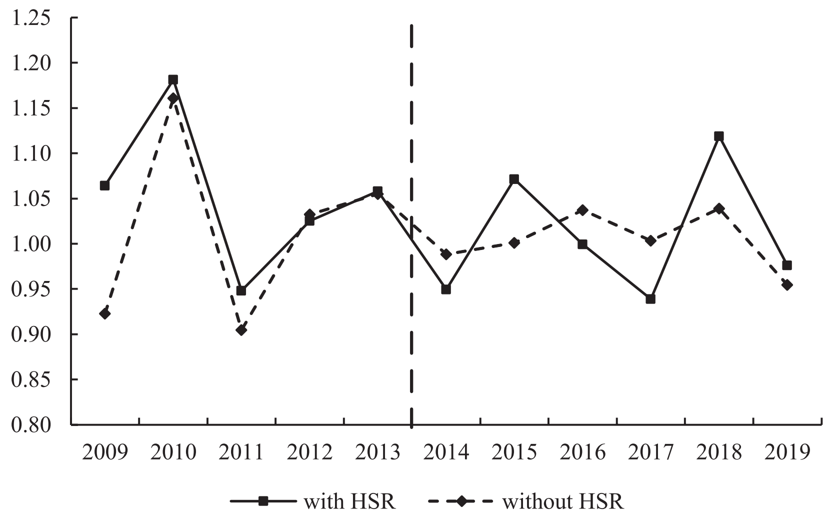

Fig. 2. Parallel trend of green innovation performance in cities with and without HSR.

Table 2. Baseline regression estimation results.

Variables	(1)	(2)	(3)	(4)
	Average effect		Dynamic effect	
HSR	0.0499***	0.0318***		
	(0.0044)	(0.0069)		
$HSR \times YEAR_1$			0.0139**	0.0044*
			(0.0075)	(0.0076)
$HSR \times YEAR_2$			0.0329***	0.0207***
			(0.0075)	(0.0078)
$HSR \times YEAR_3$			0.0366***	0.0251***
			(0.0075)	(0.0079)
$HSR \times YEAR_4$			0.0446**	0.0275*
			(0.0098)	(0.0100)
$HSR \times YEAR_5$			0.0455***	0.0315***
			(0.0075)	(0.0084)
LnIS		-0.0481***		-0.0470***
		(0.0174)		(0.0188)
LnGOV		-0.0029*		-0.0044
		(0.0090)		(0.0087)
LnFDI		0.0015*		0.0021*
		(0.0032)		(0.0032)
LnHUM		0.0010		0.0025
		(0.0097)		0.0096
LnTEC		0.0239***		0.0225***
		(0.0052)		(0.0051)
Constant	0.8789***	0.3779***	0.3841***	0.4199***
	(0.0030)	(0.0050)	(0.0025)	(0.1349)
Time FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
R^2	0.4114	0.7176	0.6550	0.6886
N	1188	1188	1188	1188

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1%, respectively.

shows that the dummy variables are significantly positive at the 1% level regardless of the inclusion of control variables, and the opening of HSR improves regional green innovation performance by 3.18%, which is about 0.29% per year on average, and the Hypothesis 1a is verified.

For each control variable, the estimated coefficient of industrial structure is significantly negative at the 1% level, indicating that the current transformation and upgrading of industrial structure is not conducive to the improvement of green innovation performance. The estimated coefficient of government intervention is significantly negative. Generally speaking, government financial expenditure contributes to improving urban transportation infrastructure and calling on residents to choose more environmentally friendly public transportation, but this effect is not achieved at present, probably due to the low proportion of transportation infrastructure in government financial expenditure. The estimated coefficient of FDI is significantly positive, and the more open the economy is, the more favorable it is to invest in innovation resources and the introduction of advanced green innovation technologies, and a higher level of foreign direct investment can effectively improve green innovation performance. Human capital is still insignificant at the 10% level, implying that the current human resources do not give enterprises a guarantee of green innovation talent, which is not conducive to the improvement of green innovation performance. The estimated coefficient of technological progress is significantly positive, implying that technological progress has contributed to green innovation performance at the present stage.

According to Eq. (2), the dynamic effect of HSR on regional green innovation performance can be further examined, and the results are shown in columns (3)-(4) in Table 2. The enhancement effects of HSR on regional green innovation performance in the five years after HSR opening are 1.39%, 3.29%, 3.66%, 4.46% and 4.55%, respectively, with a distinct upward trend, indicating that the opening of HSR has a significant time-dynamic effect on regional green innovation performance enhancement, and this conclusion still holds after adding control variables. Therefore, Hypothesis 4 is verified.

Mechanism Result

To further verify whether HSR affects knowledge spillover through factor flow, which in turn affects regional innovation and ecological environment and ultimately promotes green innovation performance, Equations (4)-(6) are regressed separately. Meanwhile, the share of indirect effects is given based on Bootstrap test for robustness, and the results are shown in Table 3.

Table 3. Mechanism result.

Variables	(2)	(5)	(6)
	GE	PFL	GE
HSR	0.0318***	0.5296***	0.0217***
	(0.0069)	(0.0577)	(0.0070)
PFL			0.0189***
			(0.0034)
Control	Yes	Yes	Yes
Constant	0.3779***	2.7770***	0.3254***
	(0.0050)	(0.0422)	(0.0107)
Time FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Sobel test		0.0100***	
		(0.0021)	
Bootstrap test(ind_eff)		0.0100***	
		(0.0019)	
Bootstrap test(dir_eff)		0.0217***	
		(0.0071)	
ind_eff proportion		31.54%	
R^2	0.7176	0.6665	0.6420
N	1188	1188	1188

Column (2) in Table 3 shows that the total effect of HSR opening on green innovation performance is 0.0318 and is significant at the 1% level, which is consistent with the conclusions drawn in the previous section. Column (5) gives the estimated results of the effect of HSR opening on factor flow, and the regression coefficient is significantly positive at the 1% level, indicating that HSR opening increases inter-regional factor flow, which is conducive to improving regional green innovation performance. Column (6) depicts the estimated results of factor flow on green innovation performance, and the regression coefficient is significantly positive at the 1% level, implying that factor flow further contributes to the improvement of green innovation performance. In summary, the opening of HSR improves the level of factor flow and thus regional enhancement of green innovation performance. The mediating effect is 0.0100, accounting for about 31.53% of the total effect. Sobel test and Bootstrap test are both significant at the 1% level, and the mediating effect of factor mobility exists significantly. Therefore, Hypothesis 1b holds.

Heterogeneity Test

Geographical Location

The results of the above confirm that the opening of HSR can significantly improve regional green innovation performance. However, the Yangtze River Economic Belt covers 9 provinces and 2 cities. Cities in different locations have great differences in resource endowment, technological level, policy implementation, and foreign investment attraction. The regression based on the overall sample of cities may conceal regional differences. Therefore, the sample is divided into the upstream Cheng-Yu urban agglomeration, the midstream urban agglomeration and the downstream Yangtze River Delta urban agglomeration according to the cities' geographical locations, and group regression is applied to examine the differential impact of HSR opening on regional green innovation performance, and the results are shown in Table 4.

From columns (7)-(9) in Table 4, it can be seen that the opening of HSR has the most obvious promotion effect on the Cheng-Yu urban agglomeration. There may be three reasons for this phenomenon: Firstly, the Cheng-Yu urban agglomeration is the economic center of western China, with a superior natural endowment, better industrial foundation, more HSR stations, and the network system established within the urban agglomeration allows more cities to obtain the benefits of HSR. Secondly, the opening of HSR makes inter-regional economic ties more frequent, promotes the flow of innovation factors, creates convenient conditions for upstream areas to actively undertake industrial transfer from downstream areas, accelerates industrial transformation and upgrading in the Cheng-Yu urban agglomeration, and contributes to the improvement of green innovation performance. Finally, due to the geographical proximity to the midstream urban agglomeration, the external effects and spatial spillover effects will further enhance its green innovation performance.

For the midstream urban agglomeration, the green innovation performance is at a high level during the study period, but it does not have additional room for growth in the short term due to its relatively developed level of green innovation. Therefore, although the HSR network is relatively well developed, its impact on green innovation performance is not as great as that of the Cheng-Yu urban agglomeration.

The coefficient of HSR for the Yangtze River Delta urban agglomeration is 0.0261 and significant only at the 10% level, indicating that the HSR benefits of the Yangtze River Delta urban agglomeration are the smallest among the three major urban agglomerations,

Table 4. Heterogeneity test estimation results.

Variables	Geographical location			City size		
	(7)	(8)	(9)	(10)	(11)	(12)
	Cheng-Yu urban agglomeration	Midstream urban agglomeration	Yangtze River Delta urban agglomeration	Mega cities	Large cities	Small & medium cities
HSR	0.0405***	0.0294***	0.0261*	0.0420**	0.0348***	0.0110**
	(0.0116)	(0.0078)	(0.0137)	(0.0331)	(0.0115)	(0.0047)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.3592***	0.3483***	0.4194***	0.5894***	0.4035***	0.3484***
	(0.0076)	(0.0060)	(0.0103)	(0.0264)	(0.0088)	(0.0034)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.6349	0.6325	0.6079	0.6134	0.6366	0.6066
N	341	396	451	121	242	825

which may be attributed to two reasons. On the one hand, the opening of HSR attracts a large number of foreign population, and with the limited carrying capacity of cities' infrastructure, it will intensify the phenomenon of urban congestion and environmental pollution, resulting in the limited effect of HSR opening on the green innovation performance of downstream areas. On the other hand, the Yangtze River Delta urban agglomeration is located in the plain, with well-developed water, land and air transportation, and other transportation modes have substitution effects on HSR, and the higher green innovation performance also makes the additional growth space smaller. As a result, Hypothesis 2 is verified.

City Size

Studies have asserted that HSR has different effects on economic development and environmental pollution in cities of different sizes. On the one hand, large cities have a significant economic agglomeration effect with more efficient allocation and utilization of resources. On the other hand, large cities are prone to traffic congestion and environmental pollution problems [50]. Then, does the opening of HSR also have a heterogeneous impact on regional green innovation performance depending on city size? To answer this question, referring to the method of Liang et al. [51], the cities involved can be subdivided into three types, and the sample cities were classified into mega cities, large cities, and small and medium cities according to the top 10%, 10%-30%, and the bottom 70% of the regional resident population in 2014, and the regression results are presented in columns (10)-(12) in Table 4.

Columns (10)-(12) in Table 4 show the opening of HSR has a significant contribution to the green innovation performance of cities, but the contribution effect differs among cities of different sizes. The reason for this phenomenon may be related to the "siphon effect" of large cities, i.e., the opening of HSR has led to the concentration of innovation factors in large central cities and the continuous loss of resources from small and medium cities. In addition, small and medium cities usually have difficulty in improving the corresponding infrastructure construction in the short term, which ultimately leads to the weak effect of the opening of HSR on the green innovation performance of small and medium cities. Thus, Hypothesis 3 is verified.

Robustness Check

This study intends to conduct a robustness check in the following three aspects.

(1) Regression analysis based on PSM-DID method. Since there may be systematic differences between the treatment and control groups even before the opening of HSR, the propensity score matching (PSM) method is applied to address the problem of sample selection bias. The level of economic development, fixed asset investment, population density, urbanization level, and general government budget expenditure of each city were selected as covariates to be matched by the 1:1 nearest neighbor matching method, and 1173 samples were obtained. The matched samples were again subjected to DID estimation, and the results are shown in column (13) of Table 5. The results show that the coefficient of HSR opening is significantly positive at the 1% level and the double difference estimation is robust.

Table 5. Robustness tests and estimation results of the HSR network.

Variables	(13)	(14)	(15)	(16)	(17)	(18)
	PSM-DID	Sample range change	Counterfactual test			HSR network
			Advance 1-year	Advance 2-year	Advance 3-year	
HSR	0.0267***	0.0202***	0.0065	-0.0200	0.0055	
	(0.0065)	(0.0062)	(0.0046)	(0.0047)	(0.0051)	
DC						0.0722***
						(0.0066)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.3765***	0.3678***	0.3770***	0.3834***	0.3586***	0.3610***
	(0.0047)	(0.0045)	(0.0055)	(0.0062)	(0.0100)	(0.0045)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.6142	0.6099	0.5141	0.5042	0.5059	0.5379
N	1173	1067	1188	1188	1188	1188

(2) Sample range change. Given that the government will take the lead in constructing HSR in provincial capitals and municipalities directly under the central government. Compared to ordinary cities, provincial capitals and municipalities directly under the central government also invest more in environmental protection and pollution control, and the political demands bring about higher drivers of green development, leading to heterogeneity in the two groups of samples subject to policy shocks, resulting in biased results. Therefore, after removing the provincial capitals and municipalities directly under the central government from the sample cities and re-running the empirical test, the regression results are shown in column (14). It is indicated that the impact of HSR on the green innovation performance of other cities (non-provincial capitals and non-municipalities directly under the central government) is basically consistent with the baseline regression results, that is, it has a significant positive impact. This result implies that the impact of HSR opening on regional green innovation performance does not vary with sample change, and the findings of the study are robust.

(3) Counterfactual test. To further test the robustness of the regression results, a counterfactual test was conducted by changing the opening time of HSR, i.e., if HSR did not have a significant effect on regional green innovation performance, it indicated that there were no other systematic errors in the two sets of experiments and the conclusions obtained from the benchmark regression were credible. Conversely, if the effect was significant, the conclusions from the benchmark regression were not credible. Therefore, the opening time of HSR is advanced by 1-3 years for testing respectively, and the results are shown in columns (15)-(17). According to the regression results, the impact of HSR opening on regional green innovation performance is not significant after advancing the opening time of HSR, which means that before the opening of HSR, the dummy variable HSR has no impact on regional green innovation performance, and there is no systematic error. Therefore, the conclusions obtained from the benchmark model are credible.

Further Discussion

Since the above analysis can only reflect the impact of the "opening of HSR" on regional green innovation performance, it cannot cover the impact of HSR network as a whole on regional green innovation performance. Therefore, we propose to use SNA to construct a complex network structure according to the opening time of HSR, and then calculate the urban degree centrality of the HSR network and incorporate it into the DID model to further analyze its impact on the regional green innovation performance.

The HSR network structure of the Yangtze River Economic Belt in 2009, 2014 and 2019 is visualized with the support of UCINET and Netdraw software, respectively, and the results are depicted in Fig. 3. Due to the space limitation, only the structure of HSR network of Yangtze River Economic Belt in 2019

Fig. 3. 2019 Yangtze River Economic Belt HSR network structure map.

is shown here. Among which, the size of city circle area represents the size of DC, and the inter-city linkage represents the main HSR connection between cities. In 2009, Zhenjiang, Wuxi and Yueyang have the largest central nodes with direct connections to three cities, and more isolated node cities (no cities are directly connected to them). By 2014, Wuhan has the largest central node, directly connected to 5 cities, and fewer isolated node cities. As can be seen from Fig. 3, By 2019, Wuhan and Shangrao have the largest central nodes, which are directly connected to 5 cities, and the number of isolated nodes decreases to 19. It can be observed that the breadth of HSR network connections in the Yangtze River Economic Zone increased during the study period, the number of central node cities grew, and the communication capacity of the transportation vein was significantly enhanced.

By measuring the DC value of each city and replacing the HSR in the base regression, the results are shown in column (18) of Table 5. According to the regression results, it can be seen that the DC of HSR network cities can significantly promote regional green innovation performance, and the higher the DC value, the more extensive the HSR network connections are, the more likely it is to accelerate the flow of innovation factors, realize cross-regional knowledge exchange and technology spillover, and promote the diffusion of green innovation technologies. Therefore, the breadth of HSR network connections has a positive impact on regional green innovation performance. In addition, a high DC value generally implies that the city is in a transportation hub position and can attract more high-quality innovation factors. This phenomenon is more evident in the upper and middle reaches of the Yangtze River Economic Belt, while the insignificance in the lower reaches may be related to the substitution effect of HSR due to its flat topography and developed transportation.

Conclusions and Policy Implications

The opening of HSR greatly facilitates urban transportation infrastructure, accelerates the flow of innovation factors, and promotes interregional knowledge spillover, which in turn positively affects regional green innovation performance. Based on the panel data of 108 cities in the Yangtze River Economic Belt from 2009 to 2019, this paper combined DID method with mediating effect model to examine the impact of HSR opening on regional green innovation performance. The following five conclusions are obtained.

(1) The opening of HSR improves the regional green innovation performance in general. Compared with non-opening cities, the opening of HSR brings an average of 3.18% improvement to regional green innovation performance.

(2) The promotion effect of HSR on regional green innovation performance has a dynamic effect.

(3) The mediating effect indicates that the flow of innovation factors is a critical path for the opening of HSR to promote regional green innovation performance.

(4) The impact of HSR on green innovation performance is heterogeneous across geographic locations and city sizes, and is more significant in the upstream Cheng-Yu urban agglomeration and mega cities.

(5) The breadth of HSR network connection has a positive impact on regional green innovation performance, and is more pronounced in the upper and middle reaches of the Yangtze River Economic Belt.

Based on the above-mentioned findings, we draw some preliminary practical implications as follows.

(1) The construction of HSR network should be continuously promoted, the density of HSR network ought to be intensified, and the exchange of talents, knowledge and technology among regions are supposed to be strengthened, so that HSR can become a medium for the dissemination of advanced knowledge, information technology and environmental protection concepts. Then, the regional industries can be guided to develop in a cleaner and environmentally friendly direction, and the enhancement effect of HSR on regional green innovation performance can be further exploited.

(2) Since the impact of HSR on regional green innovation performance is heterogeneous among cities with different geographical locations and city sizes, it is beneficial for the Yangtze River Economic Belt to accelerate the establishment of regional organizations that promote strategic interoperability. Each city ought to formulate a joint work implementation plan based on its own location advantages and technical level, fully explore its own competitive and comparative advantages, and promote the overall improvement of the green innovation performance of the Yangtze River Economic Belt.

(3) Considering the limited effect of HSR opening on the green innovation performance of the Yangtze River Delta urban agglomeration, and the obvious substitution effect of other transportation modes for HSR. Therefore, for the Yangtze River Delta urban agglomeration, it is more necessary to implement precise policies and a rational layout, and gradually optimize the benefits of HSR instead of blindly promoting the construction of HSR networks.

(4) In view of the possible "siphoning effect" of HSR on small and medium cities, on the one hand, they should be alert to the negative impact of the "siphoning effect". On the other hand, they need to take advantage of the opportunity brought by HSR, take the initiative to undertake the transfer of quality industries from large cities, actively explore the special road suitable for their own development, realize the interconnection between small and medium cities and large cities, and create conditions for extending

regional accessibility and further exploiting the economic effect of HSR.

At the end of the study, it is mentioned that this study also has certain limitations. On the one hand, in terms of sample period selection, only 108 cities along the Yangtze River Economic Belt were analyzed from 2009 to 2019, but the impact of HSR on the regional green innovation performance is a dynamic process. Does the impact of HSR on regional green innovation performance change over time and with the gradual expansion of the sample period? On the other hand, the opening of HSR makes cities more accessible and will indirectly improve the transport situation of neighboring cities. So, is there a spatial spillover effect of the opening of HSR on regional green innovation performance? This will be the direction of future research.

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Data Availability

Data used in this manuscript is available from http://www.china-railway.com.cn,https://www.12306.cn,https://navi.cnki.net/knavi/yearbooks/YZGCA/detail and http://www.stats.gov.cn/tjsj/ndsj.

Conflict of Interest

The author declares no conflict of interest.

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