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How does high-speed railway affect green technology innovation? A perspective of high-quality human capital

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Abstract

Green development is the main theme of modern development in China and even the world. Green development depends on green technology innovation (GTI). Therefore, for developing countries like China in the stage of economic transition, it is urgent to accelerate GTI to gain sustained advantages in the new round of international competition. As an important representative of contemporary rapid transportation, high-speed railway (HSR) can not only alleviate the rapidly growing transportation demand of the public, but also have potential benefits to the energy consumption structure and environmental quality. Whether and how HSR affects GTI has become the focus of this paper. Hence, by employing the panel data of 286 cities in China from 2007 to 2018 with the time-varying DID model, this paper verifies that HSR development can contribute to GTI. The main findings of this paper are as follows: (1) The operation of HSR can not only make the incremental development of GTI, but also improve the quality of GTI simultaneously. Moreover, the quality improvement effect of HSR is greater than the quantity increment effect. (2) Heterogeneity analysis shows that the positive effect of HSR on GTI is more significant for cities that have implemented LCCP. (3) This paper verifies the mediating effect of high-quality human capital. The opening of HSR further stimulates GTI by improving the level of high-quality human capital in cities and increasing the opportunities for knowledge exchange and diffusion. Based on the above findings, this paper proposes some policy recommendations to help developing countries achieve GTI with positive externalities.

Keywords Green technology innovation, High-speed railway, High-quality human capital, Time-varying DID model, Developing countries

Introduction

After entering the twenty-first century, the world is facing the threat of continuous growth of the ecological environment. The way of economic development at the expense of the environment has been widely criticized. Therefore, promoting green development has become a common choice for all countries in the world to deal with the problems of resources, environment and climate change. The Chinese government is also striving to transform the traditional development model and actively achieve green and sustainable development. At present, China's energy structure and industrial structure are in a severe stage of structural transformation, and the task of ecological and environmental protection is still arduous. Green technology, due to its characteristics of improving energy efficiency and reducing pollution emissions, is expected to be an effective support means to help countries around the world break through environmental and resource constraints and promote green economic development [1]. In fact, the green and low-carbon transformation and upgrading of both industrial structure and energy structure cannot

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be separated from the support of green technology. Therefore, to gain sustained advantages in the new round of international competition, how to effectively accelerate green technology innovation (GTI) for developing countries like China in the stage of economic transition has become a topic worth studying.

As a competitive alternative to road and air transport, high-speed railway (HSR) has become a popular choice for Chinese citizens to travel. However, due to the very high construction and maintenance costs of HSR, and the return rate is quite low or even negative, leading to public doubts and concerns about China's large-scale construction of HSR. Therefore, in the past decade, many scholars have tried to identify various potential positive impacts of HSR development. As a new representative of rapid rail transit, HSR not only promotes the efficient development of economy and society, but also has potential impacts on both energy consumption structure and environmental quality [2, 3]. Therefore, under the background of China's emphasis on green economic and social development, whether the development of HSR can promote GTI has become the focus of this paper.

In the field of new economic geography, many scholars have theoretically and empirically analyzed the positive impact of transport infrastructure construction (including HSR development) on knowledge innovation and technology diffusion [4–7]. Although technological innovation plays an important role in improving productivity, only environmentally friendly GTI can ensure sustainable economic development [8]. At present, there are still relatively few articles that directly study the relationship between HSR and GTI. From the perspective of the flow of innovation factors, Huang and Wang [30] empirically verified that high-speed railways increase the possibility of regional green technology innovation activities by improving the attractiveness of cities to innovative talents. On this basis, Zhu et al. [31] further distinguished the impact of labor mobility and scientific research fund mobility. Lin et al. [32] analyzed from the perspective of collaborative convergence of manufacturing industry and producer services, but the data used lack of effectiveness. Zhou et al. [33] used the three heat transfer methods in physics to theoretically reveal the driving effect of high-speed railway on regional green innovation spillover. However, their results are not supported by empirical analysis and lack certain persuasive power. Hence, this paper aims to supplement the gap in this part of the research. Besides, the literature related to the influence of geography on knowledge innovation and technology spillovers emphasizes the importance of human capital [9, 10]. In the current era of knowledge economy, human capital, especially high-quality human capital, has become a key factor to explain the differences in regional innovation and economic development [11]. However, as far as the author is aware, current articles examining the relationship between HSR and GTI from the perspective of human capital focus on the flow of human capital. That is, it focuses on the cross-regional flow of knowledge and focuses on the externality of technology, rather than the spatial transfer and distribution of human capital as an innovation factor itself. In addition, studies have shown that HSR can better meet the demand for high-quality manpower that is sensitive to timeliness but not to price [12]. Compared with ordinary human capital, high-quality human capital has higher education level and is easier to master and apply new technology. Therefore, it is necessary to deeply analyze the impact of HSR development on GTI from the perspective of high-quality human capital stock.

Using the panel data of 286 cities in China from 2007 to 2018, this paper examines the impact of HSR development on GTI and the mediating effect of high-quality human capital. The potential contributions of this paper are as follows. Firstly, few studies have explored the impact of HSR development on GTI. Therefore, this paper examines the impact of HSR development on the quality and quantity of GTI, and enriches the relevant research content. Secondly, most of the literature has confused the concepts of green innovation and GTI, which is clearly defined and distinguished in this paper. Thirdly, most of the existing studies analyze the influencing mechanism of HSR development on GTI from the perspective of talent flow. This kind of research focuses on the externality of technology, rather than the spatial transfer and distribution of human capital as an innovation factor itself. Therefore, this paper examines the mediating effect of high-quality human capital stock, which provides a potential way for local governments to promote GTI.

The rest of this paper is arranged as follows: the Sect. 2 is literature review; Sect. 3 is the mechanism analysis and research hypothesis; Sects. 4 and 5 are the setting of measurement model, the selection of variables, and the source of data, respectively; Sect. 6 is the analysis of regression results; the final section presents conclusions and recommendations.

Literature review

Green innovation and GTI are two different concepts. Green innovation can be broadly defined as innovation that can bring economic value and significantly reduce negative environmental externalities, including all innovations in technology, process, product, service, production process and management [13–15]. And GTI, as an indispensable part of green innovation, plays an important role in sustainable development.

Scholars generally agree that technologies that can prevent or reduce pollutant emissions and save resource consumption in the process of production or consumption can be classified as green technologies [16], which includes technologies in energy conservation, terminal pollution treatment, waste recycling, environmental management and other aspects.

The factors affecting GTI can be divided into two aspects: internal motivation and external intervention. Internal driving forces mainly come from factors such as organizational innovation, R&D investment, enterprise size, entrepreneurship and management level [17–20]. External factors are mainly determined by variables such as environmental regulation, economic agglomeration, factor flow, industrial structure, regional integration, marketization level and green finance [21–27]. When the research perspectives are different, the internal and external driving forces affecting GTI will also be different.

In recent years, GTI has been widely recognized as an effective means to promote sustainable economic development [28, 29]. However, few studies have focused on the impact of transportation infrastructure, especially HSR development, on regional GTI. From the perspective of the flow of innovation factors, Huang and Wang [30] tested that HSR increases the possibility of regional GTI activities by improving the flow of innovative talents from cities. Zhu et al. [31] found that the opening of HSR promoted green innovation by increasing the flow of labor and research funds. Lin et al. [32] empirically showed that HSR service supply has a significant role in promoting the urban GTI capacity by promoting the collaborative agglomeration of manufacturing and producer services. In particular, cities located in central and western China, as well as those with relatively little government support or relatively backward public cultural infrastructure, have a better chance to benefit from the supply of HSR services. Zhou et al. [33] used three heat transfer methods in physics to theoretically reveal the driving effect of HSR on regional green innovation spillover. In addition, Hu et al. [34] examined that China's expressway development mainly affects regional GTI through agglomeration effect, spatial spillover effect and network effect. The above studies have proved that the construction of large-scale transportation infrastructure, especially HSR, has a significant role in promoting GTI.

Although the literature directly studying the relationship between HSR and GTI is relatively scarce, many studies have examined the relationship between HSR construction and environmental improvement. This part of the study points out that triggering technological innovation is the fundamental way for HSR to improve energy efficiency and reduce pollution emissions. Jia et al. [35] showed that HSR, on one hand, generates knowledge spillover effect by improving accessibility and promotes technological innovation in cities along the route, improves the overall technical level of the industrial chain in the agglomeration area. Zhang et al. [36] argued that HSR affects technological innovation by affecting the input of human capital and physical capital, thus reducing environmental pollution. Chen [37] showed that HSR can reduce the total energy consumption and energy consumption intensity by promoting technological innovation. It can be seen that energy conservation and emission reduction are largely restricted by industry and technology, and there is a direct and close relationship between the development of HSR and this type of technological innovation. Therefore, this paper aims to supplement the research gap on the topic of HSR development and GTI.

In addition, many studies emphasize that the level of human capital directly affects the exchange of local information and ideas, and plays a decisive role in the R&D and innovation of local green technologies [38]. At the same time, some studies have shown that local innovation subjects can also transfer the green knowledge and technology spillover from external to their own use through imitation and familiar application [39, 40]. Therefore, local high-quality human capital with higher education background or skilled technology, as the subject of innovation, not only determines its own ability to develop technological innovation, but also shoulders the responsibility of absorbing and transforming external advanced GTI, and its contribution to GTI and economic growth cannot be ignored [41–43]. Therefore, this paper further examines how the development of HSR affects high-quality human capital, thus stimulating GTI.

Mechanism analysis

HSR is a large-scale transportation infrastructure service, which has a significant and far-reaching impact on the GTI activities of cities [44]. Firstly, the impact of HSR development on GTI is inseparable from the expanded knowledge spillover effect of HSR development. The endogenous growth theory under the framework of new economic geography shows that intellectuals with common knowledge base can create new knowledge and technology through cross-regional communication and mutual learning [45]. Compared with traditional means of transportation, the most direct impact of HSR is that it can cause the flow of human capital, reduce the cost of ideas and technology exchange, thus producing significant technology spillover effect and promoting GTI [46]. Secondly, the impact of HSR development on GTI is also significantly related to the spatial distribution of economic activities reshaped by HSR.

The agglomeration of economic activities can not only make innovation opportunities more obvious, but also continuously stimulate the competition of enterprises within the cluster [47]. Therefore, the agglomeration plays a vital role in continuous innovation ability. By optimizing the allocation of production resources such as capital, information and technology among cities, the development of HSR improves the location conditions of cities and attracts the agglomeration of enterprises, thus inducing positive competition effect and stimulating GTI [48]. Then, how does the development of HSR specifically affect the high-quality human capital of cities, thus stimulating GTI?

First, HSR attracts the agglomeration of high-quality human capital by improving the economic characteristics of cities. HSR can raise urban wages, increase employment, and significantly promote economic growth [48]. Since knowledge-intensive industries tend to locate in areas with convenient transportation [49], the development of HSR can promote the agglomeration of knowledge-intensive industries, expand the market scale, and improve the allocation efficiency of high-quality human capital [50]. In general, high-quality labor will flow from regions with small market size and low labor remuneration to regions with large market size and high labor remuneration [51]. In addition, housing prices will also affect the flow of high-quality human capital by affecting the relative utility of workers [52]. However, the relationship between house prices and high quality human capital has not been clarified. Although, high housing prices mean higher living costs, which may have a crowding-out effect on high-quality human capital. However, high housing prices also mean higher expected income and return on investment, which may have a huge attraction to high-quality human capital. Therefore, the positive impact of HSR development on urban real estate prices will reshape the spatial distribution of high-quality human capital [53]. Second, the development of HSR affects the development of high-quality human capital by changing the non-economic characteristics of cities. With the continuous development of economy, people's concept of life has gradually changed. Non-economic factors that affect quality of life, such as climate, air quality, and medical services, determine the retention of high-quality talents [54, 55]. Many studies have shown that the opening of HSR also has a significant impact on factors that determine quality of life. As a cleaner means of transportation, HSR can not only emit fewer air pollutants, but also effectively improve the air quality of cities [56] and attract the migration of high-quality human capital. Moreover, Choi et al. [57] show that the supply of HSR services can help medical patients access medical care services and improve the health level of residents. Wang and Guo [58] point out that highly educated and skilled individuals, in particular, are more sensitive to changes in air quality and healthcare resources than other socioeconomic indicators. Therefore, the opening of HSR can not only attract the concentration of high-quality human capital, but also improve the health status of high-quality human capital. Third, the development of HSR breaks the barrier of factor flow caused by low transportation connectivity, and increases the opportunity for high-quality talents to communicate face-to-face across regions, thus improving the quality of high-quality human capital. On the one hand, HSR shortens commuting time and form a moderate concentration of high-quality human capital in some cities in a short period of time, realizing the sharing and dissemination of green technologies [5]. Specifically, high-quality human capital with higher skills can transfer advanced green technology and related knowledge to lower-level high-quality human capital in a timely manner. Then, the high-quality human capital that has learned and mastered the new technology can quickly and effectively spread out with the HSR network, thus improving the technical level of human capital on the whole [59]. On the other hand, the reduction of communication costs brought about by HSR also increases the possibility of regional cooperation, which helps high-quality human capital exchange heterogeneous knowledge and improve the corresponding knowledge reserve level [60]. Because more efficient finding and matching of collaborators is conducive to the formation of research collaborations. At the same time, for high-quality human capital, large spatial distance is not conducive to the exchange and cooperation of tacit knowledge. Therefore, HSR accelerates the flow of high-quality labor with high time value, stimulates the "learning effect", "exchange effect" and "imitation effect" of high-quality human capital, and improves the quality of high-quality human capital on the whole.

Setting of econometric model

Benchmark regression model

At present, most of the research on HSR regards the construction of HSR as a "quasi-natural experiment", and then combines the DID model to evaluate the effect of HSR. However, in reality, the opening time of HSR in various cities in China is not uniform, which does not meet the requirements of the traditional DID model on the consistent time point for individuals to accept policy shocks. Therefore, this paper refers to the practice of Sun and Yan et al. [3] to evaluate the effect of HSR in combination with two-way fixed effects under the framework of time-varying DID. The time-varying

DID model allows for cases where individuals in the experimental group have different time nodes to receive the policy treatment. Therefore, the model of benchmark regression in this paper is set as follows:

$$\mathrm{GTI}_{i,t} = \alpha_1 \mathrm{HSR}_{i,t} + \alpha_2 X_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t}$$

where, subscripts i and t represent city and year, respectively; $\mathrm{GTI}_{i,t}$ represents the GTI of city i in year t, including quantity and quality of GTI ($\mathrm{GTI\_Quan}_{i,t}$ & $\mathrm{GTI\_Qua}_{i,t}$), which are the core explained variables of this paper; $\mathrm{HSR}_{i,t}$ is the main explanatory variable, namely, the opening of HSR; $X_{i,t}$ is a series of control variables, including economic development (ED), financial support (GS), financial development (FD), foreign investment (FI) and communication technology development (ID); μ_i is the urban fixed effect, controlling the urban characteristic factors that do not change with time; γ_t is the year fixed effect, which is used to control the urban fixed effect of urban heterogeneity; $\varepsilon_{i,t}$ is the random error term.

Mechanism test model

To further verify the mediating effect of high-quality human capital, this paper refers to the practice of Baron and Kenny [61] and adds the following two-step test on the basis of the benchmark regression.

First, the impact of HSR development on high-quality human capital is tested:

$$\mathrm{HQT}_{i,t} = \eta_1 \mathrm{HSR}_{i,t} + \eta_2 X_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t}$$

Then, high-quality human capital is introduced into the benchmark regression model to verify the impact of HSR development on GTI after controlling high-quality human capital:

$$\mathrm{GTI}_{i,t} = \rho_1 \mathrm{HSR}_{i,t} + \rho_2 \mathrm{HQT}_{i,t} + \rho_3 X_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t}$$

where, subscripts i and t represent city and year, respectively; $\mathrm{GTI}_{i,t}$ represents GTI; $\mathrm{HSR}_{i,t}$ is the opening of HSR; $\mathrm{HQT}_{i,t}$ is the mediating variable- high-quality human capital- that this paper focuses on; The other variables are consistent with the setup of the benchmark regression.

Coefficient ρ_2 is the effect of independent variable on high-quality human capital ($\mathrm{HQT}_{i,t}$). The coefficient ρ_2 is the effect of the mediating variable ($\mathrm{HQT}_{i,t}$) on the dependent variable ($\mathrm{GTI}_{i,t}$) after controlling for the influence of the independent variable ($\mathrm{HSR}_{i,t}$), while the coefficient ρ_1 is the direct effect of the independent variable ($\mathrm{HSR}_{i,t}$) on the dependent variable ($\mathrm{GTI}_{i,t}$) after controlling for the influence of the mediating variable ($\mathrm{HQT}_{i,t}$). The mediating effect is equal to to the product of coefficients η_1 andρ_2, and they have the following relationship [62]: $\alpha_1 = \rho_1 + \eta_1 \bullet \rho_2$. If$\alpha_1, \eta_1, \rho_1$, and ρ_2 are both significant, it proves that the mediating effect exists. If α_1, η_1, and ρ_2 are both significant but ρ_1 is not significant, the existence of a full mediating effect is proved. Otherwise, we consider that the transmission mechanism does not exist.

Variables and data

Explained variables

This paper defines GTI as the innovation that contributes to related technologies such as resource conservation, energy efficiency improvement, pollution prevention and control, and sustainable development. Scholars mainly use two methods to measure GTI. The first method is to directly use the number of green patents to measure [63]. The second method is to add environment-related factors to the total factor productivity, and attempt to use the input and output efficiency values of R&D to reflect the efficiency of green technology progress. This part of the literature usually uses the method of GML index of SBM model set of unexpected output super efficiency to calculate [64]. This paper argues that the second method does not take into account the cost of environmental governance and the economic loss caused by environmental pollution, which cannot truly reflect the relationship between the input and output of GTI. On the contrary, green patents are the direct products of GTI, which can effectively reflect the level of R&D and innovation in the current year [65]. Therefore, this paper chooses to use the first method, namely the number of green patents, to measure the city's GTI. In addition, considering the long time difference between patent application and authorization, this paper finally uses the number of green patent applications as the proxy variable for GTI.

The steps for obtaining green patent application data are as follows: In the first step, the author manually collected the relevant information of various types of patents from the system of the State Intellectual Property Office, including the address of the applicant, the application time and the patent classification number. Then, the patent data are classified according to the address and time of the applicant, and the panel data are formed with the prefecture-level city as the individual unit and the year as the time unit. In the second step, according to the IPC Green List issued by the World Intellectual Property Organization, this paper selects the International Patent Classification (IPC) code related to environmentally sound technologies from all patents and defines them as green patents. The third step is to classify the obtained patent application data according to the selected IPC classification number to determine whether the patent is a green technology-related patent. Finally, this paper extracts the green patent application panel data with the prefecture level city as the individual unit and the year as the time unit.

Patents are regulated and classified differently in different countries. According to the Patent Law of the People's Republic of China, patents are divided into three types: invention patents, utility model patents and design patents. Invention patent means a new technical solution to a product, method or improvement thereof. Utility model patent means a new technical scheme which is suitable for practical use and which relates to the shape, structure or combination of the product. Exterior design patent is a new design related to aesthetic and industrial applications. The green patent application data collected in this paper do not involve the type of design, so the total number of green patent application is the sum of the number of green invention patent applications and green utility model patent applications.

Since invention patents have a more significant technological improvement and a stricter review process than utility model patents, invention patents are often regarded as an important indicator of innovation quality [66]. Referring to the practices of Dong and Wang [66] and Xiao et al. [67], this paper adopts the total number of green patent applications per 10,000 people to measure the quantity of GTI in a city (GTI_Quan), and the number of green invention patent applications per 10,000 people to measure the quality of GTI (GTI_Qua). The increase in the total number of green patent applications per 10,000 people means that there is a quantitative expansion of GTI in this city. The increase in the number of green invention patent applications per 10,000 people means that the GTI in this city has been qualitatively improved.

Main explanatory variable

Under the framework of the time-varying DID model, the variable of HSR is the binary dummy variable (HSR) of whether the city has HSR. The value of the HSR variable is 0, indicating that city i did not have a HSR in year t. On the contrary, if the value of the HSR variable is 1, it means that city i has opened a HSR in year t, and since year t, the HSR variable has taken the value of 1. In addition, this paper also uses the number of stations (station) and the number of lines (line) of HSRs as alternative indicators for robustness test. These two indicators can better reflect the basic stock of local HSR.

Mechanism variable

This paper uses the proportion of the number of students in ordinary institutions of higher learning in the urban population to measure the reserve of high-quality talents (HQT). Previous studies used to take the level of education as the standard of labor skills [68]. Mansfield [69] shows that scientific research institutions, especially universities, are also important sources of external innovation knowledge. The research departments of the university mainly transfer knowledge to the industrial research and development departments of the manufacturing industry through commercial and non-commercial channels such as invention patents, publications or conferences, creating economic benefits for the local area [10]. It can be seen that higher education reflects the development potential of a country and should be the focus of national talent training. The Chinese government encourages and attaches importance to the construction and cultivation of higher education. Therefore, it is reasonable to regard the students who are receiving higher education as the high-quality talents of the city reserve.

Control variables

The introduction of control variables can effectively mitigate the endogeneity problem caused by the lack of variables. Therefore, under the constraint of data availability, this paper introduces a series of variables that may affect GTI in the constructed model. Generally speaking, economic development provides financial guarantee and technical support for GTI. So, referring to the practice of Li et al. [70], this paper uses per capita GDP to measure the economic development level (ED) of a city. The government's financial support for scientific and technological innovation has a direct incentive effect on GTI [71]. Therefore, this paper uses the proportion of fiscal expenditure on science in GDP to measure the government's support for green technology R&D and innovation activities (GS). The financial system plays a role in the continuation of technological innovation activities and the improvement of technological innovation efficiency through information collection and analysis, risk

Table 1 Descriptive statistics of variables

VARIABLES	Obs	Mean	Std. Dev	Min	Max
GTI_Quan	3,432	−1.601	1.600	−6.309	3.515
GTI_Qua	3,432	−2.399	1.694	−6.545	2.891
HSR	3,432	0.471	0.499	0.000	1.000
ED	3,432	10.433	0.732	0.000	13.056
GS	3,432	−6.232	1.081	−8.962	0.000
FD	3,432	1.120	0.296	0.000	2.676
FI	3,432	1.351	0.784	0.000	3.832
ID	3,432	−2.120	0.912	−9.712	1.303
HQT	3,432	17.484	23.425	0.000	144.580

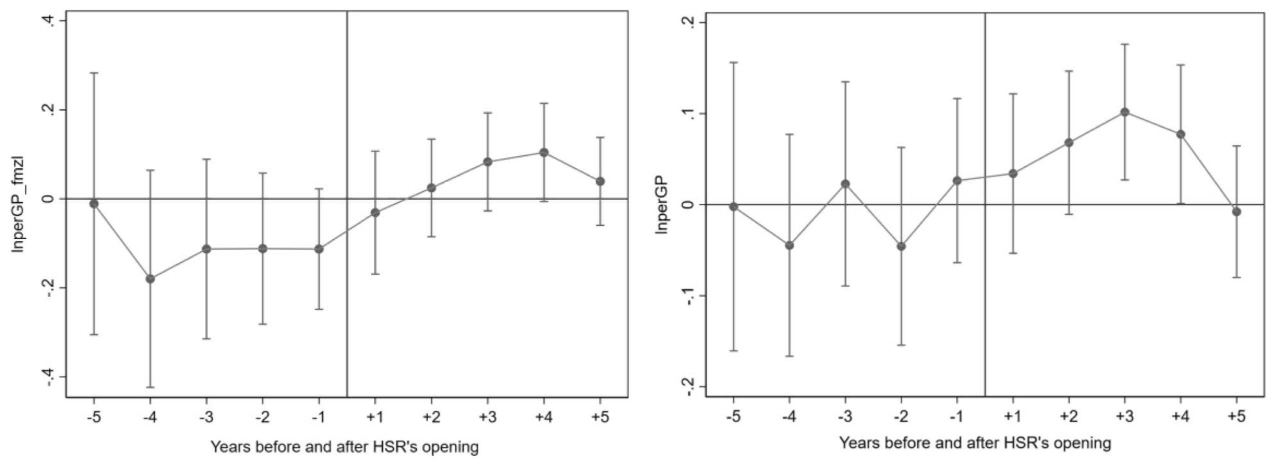

Fig. 1 Dynamic effects of HSR on the quantity and quality of GTI

diversification, credit rationing and other functions [72]. This paper uses the proportion of the total balance of deposits and loans of financial institutions in GDP at the end of the year to measure the level of financial development (FD). Besides, the importance of foreign investment in China's response to environmental pollution and promotion of green innovation cannot be ignored. According to the method of Shen et al. [73], this paper chooses the proportion of actually used foreign capital in GDP as the proxy variable of foreign investment (FI). As an information and communication technology, the rapid development of the Internet has brought new impetus to the improvement of China's green innovation level [64]. Therefore, the number of Internet users per thousand people is used as the proxy variable of Internet development (ID).

Data sources

Considering the timing of HSR construction and the availability of other related data, this paper selects 286 prefecture-level cities in China as the research objects and sets the panel time from 2007 to 2018. The time dimension ends in 2018, taking into account the significant and widespread economic and social impact of the COVID-19 pandemic at the end of 2019. Therefore, the data obtained in 2019 and after are not considered in the research scope in this paper. Green patent application data from China state intellectual property office system (https://www.cnipa.gov.cn/), while green IPC classification list is from the world intellectual property organization (WIPO). The data of HSR come from the National Railway Passenger Train Schedule from 2007 to 2018. The control variables at the city level and the data for calculating high-quality human capital are all collected from the China City Statistical Yearbook from 2008 to 2019. Some missing data are made up by linear interpolation method and average growth rate method. To solve the problem of heteroscedasticity, the explained variable, control variable and mediating variable are all treated with logarithm. Table 1 shows the descriptive statistical results of the data used in this paper.

Analysis of regression results

Preliminary inspection

The precondition for using the time-varying DID model is that the parallel trend assumption is satisfied, that is, the treatment group and the control group of cities maintain a consistent change trend before the opening of the HSR. Referring to the idea of Wang et al. [74], this paper uses the event analysis method to test whether the impact of HSR operation on the quantity and quality of GTI meets the requirements of parallel trends. The specific dynamic effect model is set as follows:

$$\mathrm{GTI}_{i,t} = \alpha_0 + \sum\nolimits_{d \geq -5}^{5} \alpha_d \mathrm{HSR}_{i,t}^{d} + \alpha_2 X_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t}$$

where, $\mathrm{GTI}_{i,t}$ is green technological innovation, including GTI_Quan and GTI_Qua; $\mathrm{HSR}_{i,t}^{d}$ is the dummy variable

Table 2 Multicollinearity test

Variable	VIF	1/VIF
ID	2.85	0.351
ED	2.29	0.436
FD	1.42	0.705
HSR	1.24	0.807
FI	1.18	0.847
GS	1.14	0.874
Mean VIF	1.69	

Table 3 The impact of HSR on GTI

Variables	(1) GTI_Quan	(2) GTI_Qua	(3) GTI_Quan	(4) GTI_Qua	(5) GTI_Quan	(6) GTI_Qua
HSR	0.105**	0.281***				
	(2.32)	(3.85)				
Station			0.022**	0.073***		
			(2.46)	(5.15)		
Line					0.074***	0.225***
					(3.10)	(5.85)
ED	0.108***	−0.045	0.108***	−0.045	0.106**	−0.052
	(2.69)	(−0.49)	(2.65)	(−0.50)	(2.51)	(−0.60)
GS	0.046***	0.033*	0.045***	0.029*	0.044***	0.028
	(3.84)	(1.93)	(3.74)	(1.70)	(3.70)	(1.64)
FD	−0.263*	−0.618**	−0.242	−0.546**	−0.226	−0.505**
	(−1.66)	(−2.49)	(−1.53)	(−2.25)	(−1.42)	(−2.14)
FI	−0.068*	−0.016	−0.071*	−0.022	−0.069*	−0.017
	(−1.70)	(−0.29)	(−1.76)	(−0.39)	(−1.72)	(−0.31)
ID	0.166**	0.169**	0.177***	0.201**	0.182***	0.215***
	(2.57)	(2.11)	(2.72)	(2.52)	(2.79)	(2.68)
Constant	−2.779***	−1.539	−2.744***	−1.481	−2.731***	−1.424
	(−5.03)	(−1.54)	(−4.96)	(−1.50)	(−4.83)	(−1.51)
Observations	3,432	3,432	3,432	3,432	3,432	3,432
R-squared	0.662	0.388	0.662	0.392	0.663	0.396
Number of cities	286	286	286	286	286	286
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes

Robust *t*-statistics in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

of the event of the opening of HSR in the city; d represents the time distance from the event of the opening of HSR, and the value range is [−5,5], representing the window period from 5 years before the opening of HSR to 5 years after the opening of HSR; α_d and β_d are the coefficients concerned in this paper, indicating the changing trend of GTI in the five years before and after the opening of HSR in cities. Considering the collinearity of variable $HSR_{i,t}^{d}$, this paper takes the initiative to eliminate the observed values in the period when HSR are opened in the city, that is, $d \neq 0$. If the city does not have a HSR in the sample period, the $HSR_{i,t}^{d}$ always takes a value of 0. The remaining variables are consistent with the setting of the benchmark regression. Figure 1 shows the specific regression coefficient and its 95% confidence interval. It can be seen from the figure that before the opening of HSR, there is no significant difference between the treatment group and the control group in terms of the quantity or quality of GTI, which meets the hypothesis of parallel trend.

In addition, all variables have passed the variance inflation factor (VIF) test using pooled OLS regression before performing the benchmark regression. The maximum value of VIF in Table 2 is 2.85, which is much less than 10, confirming the absence of multicollinearity. This paper further confirms the rationality of using the fixed effect model through the Hausman test. Therefore, it is reasonable to use the multi-period DID model with two-way fixed effects to test the impact of HSR development on the quantity and quality of GTI in this paper.

Benchmark regression analysis

Table 3 shows the regression results of the impact of HSR development on GTI. Column (1) of Table 3 shows the benchmark regression results of the impact of HSR on the quantity of GTI. According to the coefficient of the HSR, at the 5% confidence level, the opening of HSR can increase the number of green technological innovations by 10.5%. The result is consistent with the conclusion of Zhu et al. [31].

The coefficients of the control variables in Column (1) further show that the level of economic development (ED) is directly proportional to the number of GTI. At the confidence level of 1%, every 1% increase in GDP per capita will lead to a 10.8% increase in the number of GTI. This seems to confirm that economic development can provide sufficient financial support for GTI, which is conducive to the promotion of GTI [75]. The coefficient of financial support (GS) is positive at the 1% confidence level, indicating that financial support contributes to the innovation of green technology. This is consistent with the conclusion of Roh et al. [71], indicating that the government's financial subsidies and subsidies can not only send a signal to enterprises that they attach importance to GTI, but also provide financial guarantee for enterprises' innovation activities. The development of communication technology (ID) can also promote the increase in the number of GTI at the confidence level of 1%. This is consistent with the view of Paunov and Rollo [76], that is, the Internet has become the driving force of China's innovation and development, which have a positive impact on innovation efficiency. However, the empirical results of this paper show that the level of financial development (FD) and foreign investment (FI) have a significant inhibitory effect on the quantity of GTI, reducing the quantity of GTI by 26.3% and 6.8%, respectively, at the 10% confidence level. This may be because funds, both domestic and foreign, circulate only among institutions in the financial system rather than the real economy. Hence, financial institutions have not effectively alleviated the problem of corporate financing, thus failing to effectively promote GTI.

Column (2) of Table 3 shows the benchmark regression results of the impact of HSR on the quality of GTI. The regression coefficient of HSR is 0.281 and significant at the 1% confidence level. It means that the opening of HSR in cities can improve the quality of GTI by 28.1%. Therefore, this paper claims that the development of HSR can not only make the incremental development of GTI, but also improve the quality of GTI simultaneously, which is consistent with the previous analysis. Meanwhile, by comparing the coefficients of HSR, this paper finds that the quality improvement effect of HSR operation on GTI is greater than the quantity increment effect.

From the coefficients of the control variables in Column (2), it can be seen that financial support (GS) and communication technology development (ID) are also important factors for improving the quality of GTI, which can improve the quality of GTI by 3.3% and 16.9% at the confidence levels of 10% and 5%, respectively. However, the level of financial development (FD) is not conducive to the quality improvement of GTI. At the 5% confidence level, the higher the level of financial development, the worse the quality of GTI. However, this paper cannot find any evidence that economic development and foreign investment affect the quality of GTI.

Table 4 Solving the endogeneity problem

Variables	(1) IV-GMM GTI_Quan	(2) IV-GMM GTI_Qua
HSR	1.614***	2.981***
	(3.34)	(3.49)
Observations	3,432	3,432
R-squared	0.496	0.300
Number of city code	286	286
Control variables	Yes	Yes
City FE	Yes	Yes
Time FE	Yes	Yes
Under identification test	0.000	0.000
Weak identification test	10.62	10.62
Hansen J statistic	0.620	0.556

Robust *z*-statistics in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Furthermore, to improve the reliability of the estimation results, this paper uses the number of HSR stations (station) and the number of opened lines (line) to replace the dummy variable of HSR for robustness test. Columns (3–6) of Table 3 report the specific regression results. It can be seen from the coefficient that the number of HSR stations (station) can have a positive stimulating effect on the quantity and quality of GTI at the significance levels of 5% and 1%, respectively. The number of HSR lines (line) can improve both the quantity and quality of urban GTI at the significance level of 1%. After replacing the core explanatory variables, the promotion effect of HSR development on GTI is still robust.

Solving the endogeneity problem

Although panel data can solve the problem of missing variables caused by individual heterogeneity, due to the non-randomness and missing variables in the location selection of HSR stations, this paper needs to use instrumental variable method to alleviate the problem of endogeneity.

Referring to the practice of Chen et al. [77] and Lan et al. [78], this paper looks for appropriate instrumental variables from the perspectives of climatic conditions and historical factors. First, the city's climatic conditions, such as temperature, relative humidity, and precipitation, are highly exogenous. But, climate change will affect the cost and ease with which direct HSR can be built. Secondly, there is no correlation between whether there were post stations in the Ming Dynasty and the current development of GTI. The location of Courier stations in the Ming Dynasty was mostly located in the area with flat terrain, while the construction of HSR also had strict requirements on terrain, especially slope. Hence, cities with post stations built in the Ming Dynasty are more likely to build HSR, which is highly correlated. In addition, considering that the post stations in the Ming Dynasty are a set of cross-sectional data, this paper finally constructs three new panel instrumental variables, including MingTemp, MingHumid and MingPreci, by multiplying the dummy variable of whether the post stations were built in the Ming Dynasty (Ming) with climatic factors. Since the number of instrumental variables is larger than the number of endogenous explanatory variables, this paper uses the more efficient generalized method of moments (GMM) for estimation.

Table 4 reports the results of the relevant tests and regressions. The unidentifiable test, weak instrumental variable test and over-identification test (Hansen J statistic) all show that the selected instrumental variable is valid. It can be seen from the coefficient of the HSR variable that after the instrumental variable is used, it still remains significantly positive at the confidence level of 1%, indicating that the conclusion of this paper that HSR development improves the level of green technological innovation is robust and reliable.

Table 5 Heterogeneity analysis—whether it is an economically developed region

Variables	(1) GTI_Quan	(2) GTI_Quan	(3) GTI_Qua	(4) GTI_Qua
HSR	0.107**	0.110**	0.284***	0.241***
	(2.40)	(2.35)	(3.93)	(3.28)
LCCP	0.232***	0.245***	0.305**	0.060
	(3.51)	(2.60)	(2.42)	(0.26)
HSR#LCCP		0.019**		0.348*
		(2.24)		(1.75)
ED	0.107***	0.106***	−0.047	−0.038
	(2.75)	(2.71)	(−0.50)	(−0.41)
GS	0.045***	0.045***	0.031*	0.031*
	(3.78)	(3.78)	(1.85)	(1.85)
FD	−0.232	−0.234	−0.577**	−0.551**
	(−1.49)	(−1.49)	(−2.35)	(−2.23)
FI	−0.065	−0.065	−0.013	−0.017
	(−1.64)	(−1.64)	(−0.24)	(−0.31)
ID	0.181***	0.181***	0.189**	0.194**
	(2.78)	(2.77)	(2.31)	(2.38)
Constant	−2.757***	−2.752***	−1.511	−1.596
	(−5.13)	(−5.09)	(−1.48)	(−1.56)
Observations	3,432	3,432	3,432	3,432
R-squared	0.664	0.664	0.392	0.393
Number of cities	286	286	286	286
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes

Robust *t*-statistics in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Heterogeneity analysis

The purpose of green technology innovation is not to increase economic output and has no profit advantage. Therefore, organizations need external stimulus and guidance from the government to alleviate the inertia of green technology innovation activities [79]. According to the new Keynesian economic theory [80] and Porter's hypothesis [81], environmental regulation can stimulate enterprises to carry out green technological innovation activities. Therefore, from the perspective of environmental regulation, this paper studies the influence of the degree of government intervention on the relationship between HSR development and green technology innovation.

In recent years, many scholars have conducted relevant research and evaluation on the impact of low-carbon city pilot policies (LCCP) on green and non-green technology innovation. LCCP is an environmental policy issued by the National Development and Reform Commission for the purpose of reducing carbon emissions and improving energy efficiency. The policy released three batches of pilot lists of low-carbon cities in 2010, 2012 and 2017, involving more than 110 prefecture-level cities. The named cities need to focus on low-carbon economy and promote green development. Most of the evidence shows that low-carbon city pilot policies can promote green technology innovation [75].

Therefore, based on the research of Cheng et al. [82], this paper finally constructed the dummy variable of LCCP, and set 2012 as the policy experiment period of LCCP. If city i belongs to the named cities and the time is after 2012, the value of LCCP is 1; Otherwise it's all 0. In addition, by introducing the government intervention variable (LCCP) and its interaction term (HSR#LCCP) with the HSR on the basis of fundamental regression, this paper evaluates the impact of government environmental policy intervention on the relationship between high-speed railway development and green technology innovation. Specific regression results are reported in Table 5.

Column (1) of Table 5 examines the impact of LCCP on the number of green technology innovations. It can be seen from the results that the implementation of LCCP can significantly increase the number of green technology innovations. Column (2) examines the moderating effect of LCCP on HSR and the number of green technology innovations. The coefficient of the interaction term between HSR and the LCCP (HSR#LCCP) is 0.019 and is significantly positive at the 10% confidence level. This means that the moderating effect of the LCCP is

Table 6 Mediating effects of high-quality human capital

Variables	Quantity of GTI			Quality of GTI		
	(1)	(2)	(3)	(4)	(5)	(6)
	GTI_Quan	HQT	GTI_Quan	GTI_Qua	HQT	GTI_Qua
HSR	0.105**	1.570***	0.093**	0.281***	1.570***	0.273***
	(2.32)	(2.79)	(2.07)	(3.85)	(2.79)	(3.74)
HQT			0.008***			0.005*
			(3.08)			(1.82)
Constant	− 2.779***	6.713**	− 2.829***	− 1.539	6.713**	− 1.573
	(− 5.03)	(1.99)	(− 5.23)	(− 1.54)	(1.99)	(− 1.57)
Observations	3,432	3,432	3,432	3,432	3,432	3,432
R-squared	0.662	0.171	0.663	0.388	0.171	0.389
Number of cities	286	286	286	286	286	286
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes

Robust *t*-statistics in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

significantly positive, and its implementation can significantly increase the number of green technology innovations in HSR cities.

Column (3) of Table 5 examines the impact of LCCP on the quality of green technology innovation, while column (4) examines the moderating effects of LCCP on HSR and the quality of green technology innovation. The results also show that the implementation of LCCP can significantly improve the quality of green technology innovation, and has a significant positive moderating effect on the quality improvement of HSR.

To sum up, this paper believes that the implementation of LCCP has a significant role in promoting green technology innovation. Moreover, for cities that have implemented LCCP, the development of HSR will be able to further significantly promote green technology innovation.

Mechanism test

According to the setting of the intermediary effect model constructed by the "three-step method", this paper introduces high-quality human capital to test the relationship among HSR, high-quality human capital and GTI. Table 6 fully reports the three-step regression results of the mediation effect model.

Columns (1) and (4) of Table 6 report the impact of HSR operation on the quantity and quality of GTI, respectively, which is consistent with the content of the benchmark regression. Columns (2) and (5) both report the estimated results of the opening of HSR on high-quality human capital. That is, the opening of HSR can promote the increase of high-quality human capital in cities by 157% at the confidence level of 1%. This means that the development of HSR is an important factor to improve the high-quality human capital of the city. Columns (3) and (6) report, respectively, the effects of the opening of HSR on the quantity and quality of GTI after adding the variable of high-quality human capital.

Firstly, this paper observes the coefficient changes from column (1) to column (3) of Table 6. According to the coefficient in Column (3), after adding the variable of high-quality human capital, the coefficient of HSR decreases from 0.105 in column (1) to 0.093, while the significance remains at the confidence level of 5%. This shows that the opening of HSR can stimulate the growth of the number of GTI by improving the high-quality human capital of cities. At this time, the mediating effect of high-quality human capital is about 0.012. The coefficient of high-quality human capital in Column (3) is 0.008 and passes the significance test of 1%, indicating that for every 1% increase in high-quality human capital, the number of GTI will increase by 0.8%.

Secondly, this paper compares the coefficient changes in columns (4) to (6) of Table 6. According to the coefficient in column (6), after adding the variable of high-quality human capital, the coefficient of HSR decreases from 0.281 in column (4) to 0.273, while the significance is still maintained at 1% confidence level. This indicates that the opening of HSR can promote the improvement of the quality of GTI by enhancing the high-quality human capital of the city. At this time, the mediating effect of high-quality human capital is around

0.008. In column (6), the coefficient of high-quality human capital is 0.005 and passes the significance test of 1%, suggesting that the quality of GTI will be improved by 0.5% for every 1% increase in high-quality human capital.

To sum up, this paper verifies the mediating effect of high-quality human capital. With the development of HSR, the higher the high-quality human capital of a city is, the stronger its inherent learning ability is. It can not only better transform the local R&D input into GTI results, but also better absorb the GTI results obtained from the outside, thus stimulating the growth of GTI. Therefore, this paper argues that the development of HSR further stimulates the progress of GTI by increasing the level of high-quality human capital in a city, thereby increasing the opportunities for knowledge exchange and diffusion.

Conclusion and suggestion

Based on the data of 286 cities in China from 2007 to 2018, this paper uses the time-varying DID model to estimate the impact of HSR operation on GTI. The main findings of this paper are as follows: (1) The opening of HSR has significantly improved the level of urban GTI. Specifically, at the 5% confidence level, the opening of HSR can increase the number of GTI by 10.5%. At the confidence level of 1%, the opening of HSR in cities can improve the quality of GTI by 28.1%. It means that the opening of HSR can not only increase the quantity of GTI, but also improve the quality of GTI simultaneously. Moreover, the quality improvement effect of HSR is greater than the quantity increment effect. After a series of robustness tests, the conclusion is still valid. (2) Through heterogeneity analysis, this paper finds that the promotion effect of high-speed rail on green technology innovation is more significant for the cities that have implemented LCCP. (3) By constructing the mediating effect model of the three-step method, this paper verifies the mediating effect of high-quality human capital. That is, by improving the level of high-quality human capital in cities, the opening of HSR increases the opportunities for knowledge exchange and diffusion, and further stimulates GTI.

This paper verifies that the large-scale construction of HSR in China will promote the development of GTI. Therefore, based on the conclusions, this paper puts forward the following suggestions, which are helpful for developing countries to implement more effective supporting policies to achieve GTI with positive externalities.

First, the construction of HSR network should be steadily promoted to release the potential of transportation to guide the development of GTI. For developing countries, vigorously developing modern rapid transportation and building a comprehensive transportation hub integrating HSR, aviation and urban public transportation will help break down urban boundaries and truly realize urban internal and external connectivity. Because the qualitative leap in transportation can significantly promote the two-way flow of GTI elements between local cities and non-local cities, thus improving the overall level of regional and even domestic GTI.

Second, while developing HSR, the government should introduce a plan for the training and introduction of high-quality talents to eliminate the obstacles that hinder the flow of high-quality talents and improve the ability to absorb high-quality talents. For example, by promising a talent introduction plan with better conditions, ensuring welfare such as medical and educational resources, and building leisure facilities such as museums, cinemas, star-rated hotels and parks, the city can attract high-quality talents with better urban quality. In addition, in cities with high quality human capital, local governments should take advantage of the advantages of HSR network to encourage local enterprises, universities and scientific research institutions to jointly build industry-university-research platforms, promote the integration and sharing of information and resources, and promote the precise docking of green industrial chain and GTI chain.

There are still some shortcomings in this study, which are expected to be further supplemented in future study and research: the first deficiency is the limitation of data, especially the relevant data of green patents. In fact, the number of patent citations can better reflect the economic value and technical complexity of a patent. Therefore, newer and more comprehensive data can be obtained in the future to deeply analyze the essential impact of HSR development on the development of GTI. The second limitation is insufficient at the research level. The main bodies of GTI are still enterprises, universities and research institutions. Therefore, in the future, we can consider using the micro enterprise database or the patent statistics of Chinese universities to further explore whether the development of HSR can directly affect the GTL behavior of micro individuals, promote the collaborative innovation of micro individuals, and enhance the overall level of GTL.

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Declarations

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