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Original Research

Research on the Effect and Mechanism of the Opening of High-Speed Rail on City-Level Air Quality

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Abstract

The massive construction of high-speed rail has profoundly changed China, and it has also had a significant impact on air pollution in Chinese cities. Based on the panel data of 278 cities in China from 2003 to 2019, this paper makes an empirical study on the influence of high-speed rail on city-level air quality by using the opening of high-speed rail as a quasi-natural experiment and taking the method of progressive DID estimation model. The results show that: 1) The opening of high-speed rail significantly improves city-level air quality, and the conclusions are still valid after a series of robustness tests and dealing with endogenous problems. 2) The opening of high-speed rail has a heterogeneous effect on air quality in cities of different regions and different scales. 3) The opening of high-speed rail can promote technological progress and accelerate the upgrading of industrial structures, as well as reduce air pollution levels in neighboring cities through the spillover effect. 4) The opening of high-speed rail improves urban air quality through the substitution effect of air passenger transport.

Keywords: HSR (high-speed rail), air quality, technological progress, industrial structure

Introduction

Since the opening of the Beijing-Tianjin Intercity Railway in 2008, the development of China's high-speed rail has gained rapid momentum. By the end of 2021, the total mileage of China's high-speed railway exceeded 40,000 kilometers, and the construction plan of the "four horizontal and four vertical" high-speed railway network has been completed ahead of schedule. While the number of cities with high-speed railways in China continues to increase, the air quality of Chinese cities is also improving year on year, with a significant increase in the proportion of cities meeting national air quality standards. The severity of haze pollution in China reached its peak in 2013. According to the Report on the State of the Ecology and Environment in China (2013), among the seventy-four cities scheduled to enforce new ambient air quality standards at Stage I, only three cities Haikou, Zhoushan, and Lhasa attained air quality standards, which accounted for 4.1%, the nonattainment cities reached 95.9%. By contrast, statistics in the Report on the State of the Ecology and Environment in China (2020) show that compared to 2013, when the haze was at its worst, China's ecological environment quality has improved markedly. Out of all the 337 cities at or above prefecture-level (APL cities)

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across the country, 202 cities met national air quality standards, taking up 59.9%. The growth trend of China's high-speed rail mileage and air quality compliance is shown in Fig. 1. From 2013 to 2020, the mileage of high-speed rail is increasing, and so is the proportion of cities that meet air quality standards. Both are changing in similar trends. Fig. 2 shows the concentration changes of six major pollutants in the atmosphere from 2013 to 2020. Except for O_3, the concentration of other pollutants shows an obvious downward trend. Considering the continuous expansion of high-speed rail construction in recent years, high-speed rail has had a profound impact on China, and exerted an important impact on residents' daily life, enterprises' production activities, economic development and social operation. Therefore, this paper speculated that the opening of high-speed rail is also closely related to urban air quality. We combine the changes in urban air quality and mileage of high-speed rail in recent years and put forward the following questions: As a combination of various high technologies, will the opening of the high-speed rail contribute to the improvement of urban air quality? If so, then what are the specific mechanisms of this impact?

Over the past 40 years of reform and opening-up, China has rapidly risen to economic growth and achieved world-renowned results. However, the past crude development mode, which aimed at pursuing development speed at the expense of the environment, has brought about economic take-off as well as serious environmental problems. With the destruction of the ecological environment, the deterioration of air quality, and the repeated occurrence of hazy weather, people's health has been endangered and their living environment and quality of life have been greatly affected. Urban air pollution level in China has been high since 2000, with annual average $PM_{2.5}$ concentrations above 35 ug/m^3 in all years, far exceeding the upper limit of 10 ug/m^3 in WHO Global Air Quality Guidelines [1]. The growing environmental problems have raised the concern of the CPC and the government. In 2015, General Secretary Xi Jinping proposed a new development philosophy emphasizing innovation, coordination, green, openness, and sharing for all. He pointed out that economic construction and development should be guided by this concept to build a modern economic system. At present, China has gradually abandoned its previous crude development

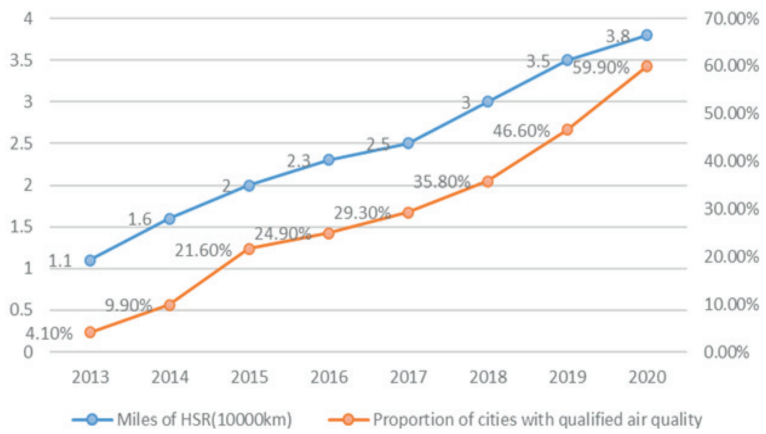

Fig. 1. 2013-2020 China's high-speed rail mileage and air quality compliance.

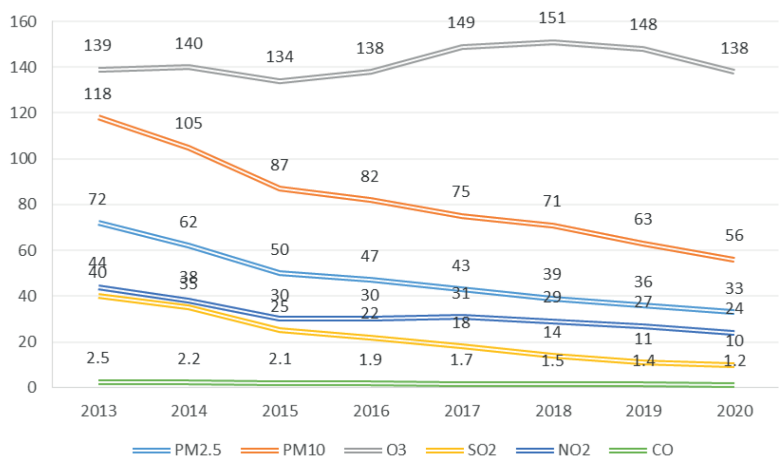

Fig. 2. 2013-2020 China's concentration of main pollutant.

mode and entered the stage of pursuing high-quality development. Therefore, it is of great theoretical and practical significance to further study the impact of the opening of high-speed rail on urban air quality.

China is a large industrial country with its production of steel, cement, coal, and non-ferrous metals ranking among the highest in the world. For a prolonged period, the country's economic development has been dependent on both natural resources and fossil energy. As a result, the high level of pollution and emissions from industrial production is one of the main factors affecting air quality. In addition, motor vehicle emissions are also a contributing factor to air pollution. By the end of 2020, China's vehicle ownership had reached 280 million, ranking first in the world. The continuous increase in the number of cars in the city has raised the total amount of exhaust emissions, exacerbating the problem of urban haze pollution. Meanwhile, the pressure on urban traffic has increased consequently and traffic congestion has become more frequent. Traffic jams on urban roads make motor vehicles idle for too long, which in turn further increases motor vehicle emissions. For the proportional distribution of sources of urban haze pollution, one study took Beijing as an example and found that the main sources of $PM_{2.5}$ in this city were secondary, coal combustion, urban raised dust, motor vehicle emissions, industrial sources, and construction dust, with respective annual average contributions of 42%, 19%, 19%, 10%, 6% and 4% [2]. To reduce the negative impact of high motor vehicle emissions and urban traffic congestion on air quality, other transportation options such as rail traffic, electric vehicles, and BRT is rapidly developing in China's major cities, which would help to reduce pollution and emissions. Traffic congestion in the city can also be improved. The opening of urban rail transit has a notable emission reduction effect on air pollution, which will grow with the increase in urban population scale, density, and pollution level [3]. The opening of BRT lines has a similar emission reduction effect to the opening of urban rail transit, but for more economically developed cities with a population of over 5 million, the environmental effect of BRT opening is minimal [4]. In addition, the large-scale promotion of electric vehicles in cities can also bring positive environmental benefits [5]. By analogy with urban rail and BRT, we speculate that the opening of urban high-speed rail would have a similar environmental effect.

Possible contributions of this paper. 1) In terms of the division of the sample, considering the geographical differences between the north and the south of China, we divided cities into two parts belonging to the south and the north respectively according to the provincial administrative area. Then we use heterogeneity analysis to study the heterogeneous impact of the opening of high-speed rail on their air quality. And since cities vary in size, we divide the sample into three main categories: large cities, medium-sized cities, and small cities, and then analyze the impact of the opening of HSR on them. The results of heterogeneity analysis have important guiding significance for the government's high-speed railway construction planning. 2) In terms of the methodology, this paper identifies the opening of HSR in each city as a quasi-natural experiment. Given the variation in the opening of HSRs from city to city, the paper uses a progressive DID model to assess the pollution abatement effects of HSR opening. To address the potential endogeneity issue, an interaction term between the average urban gradient and the annual urbanization rate in China is used as an instrumental variable for the opening of HSR. In the mechanism test, considering the possible endogeneity of the mediating effect model of the three-step method, this paper adopts the two-step method to analyze the internal mechanism of the effect of high-speed rail opening on air quality.

Literature Review

A large number of studies have been conducted by scholars at home and abroad on the impact of the opening of high-speed railways, mainly focusing on its relationship with regional economic growth, the concentration of production factors, technological progress, upgrading of industrial establishments, and accessibility. A foreign study has shown that the founding of KTX (Korea Train Express), an HSR-like transportation system, has improved people's quality of life and is beneficial to the economy of the corresponding regions. [6] Most domestic studies also agree that high-speed rail has a growth effect on the economic development of cities. The opening of high-speed rail improves inter-city accessibility and greatly shortens the time distance between cities, which in turn promotes the flow of social factors such as population and resources, and enhances the exchange and sharing of talent, technology, and other resources between cities [7]. The research of [8] confirmed the promoting effect of high-speed railway opening on technological progress, and such technological progress was represented as neutral technological progress. [9] hold that the opening of high-speed railway accelerates the flow of high-quality talents and other innovation factors among cities, promotes the flow of knowledge and technology factors, strengthens the learning effect between regions, and leads to knowledge spillovers. Inter-regional knowledge flow and knowledge spillovers are the preconditions for regional innovation activities. [10] studied the resource reallocation effect of transportation infrastructure from three aspects: factor flow, market access and production transfer, and confirmed that the opening of high-speed railway is conducive to improving the efficiency of urban resource allocation and alleviating the distortion degree of factor allocation. [11] believe that the opening of high-speed railway can promote the upgrading of local industrial structure, mainly because high-speed railway accelerates the flow of labor and capital factors between regions, which is conducive to the improvement of the reallocation effect of capital and labor, so as to realize the upgrading of regional industrial structure. [12] studied the path of high-speed rail to promote industrial structure upgrading from three aspects: division of labor effect, convergence effect and learning effect.

However, now there are relatively few studies on the effects of HSR on urban air quality both in China and abroad. Few foreign studies have been conducted on the environmental effects of HSR opening and most of the existing studies are conducted by using the method of Life Cycle Assessment (LCA). For example, [13] use the Houston-Dallas Corridor in Texas, USA, as an example to conduct a preliminary environmental life cycle assessment. After comparing the assessed results from the HSR system with similar LCA results of highway and air modes, they find that high-speed rail has contributed significantly lower GHG emissions than other vehicles in all life cycle stages except for PM. Based on the life cycle assessment method, [14[assess the total life cycle environmental impact of the planned high-speed rail line from Lisbon to Porto, in Portugal. It includes the impact of the seven main processes of train manufacturing, train operation, train maintenance, etc. Results show that the operation and manufacturing process is the first and second-largest contributor to total environmental emissions. Domestic studies on the effects of high-speed rail opening on urban air quality are as follows. [15] analyze the impact of haze pollution from two perspectives the opening of high-speed rail and urban sprawl. They find that the opening of high-speed rail has a suppressive effect on haze pollution, while urban sprawl, on the contrary, exacerbates the haze pollution problem in cities. [16] find that the opening of high-speed rail has the economic effects of both emission reduction and efficiency enhancement. From the perspective of the impact on the green restriction of the urban production system, [17] find High-speed railway's opening can reduce the pollution of the city and promote the development of the city green through the optimization of industrial structure effect, technological progress effect, opening-up expanding effect. Based on social network analysis and DID model, the study conducted by [18] shows that the opening of HSR has a notable haze mitigation effect. Also, the more HSR lines are opened and the more extensive the network connection is, for cities, the more significant the effect is. [19] employ the regression discontinuity design to study the impact of the Beijing-Shanghai high-speed railway. The results show that the opening of the Beijing-Shanghai high-speed rail has significantly improved the air quality of the cities along the route. From the perspective of a low carbon economy, [20] find that the opening of high-speed rail reduces the carbon emission intensity of cities along the route, and the effect has an average three-year lag. [1] find out that in cities where high-speed railways were opened, the PM2.5 concentration on the surface was reduced by 1.8% on average. They also studied the impact of the opening of HSR on urban haze pollution through scale effect, structure effect, and technology effect.

In general, the existing literature on the environmental effects of the opening of high-speed rail mainly adopts DID, RDD and other methods to carry out empirical research, and most of the research results have confirmed the effect of high-speed rail on reducing pollution and emission. In the mechanism analysis, most of the literature conducted the test from the aspects of industrial structure, technological progress, scale effect and foreign investment, but few literatures further tested the spatial spillover effect of industrial structure and technological progress in the mechanism test. Therefore, in the mechanism test of this paper, the spatial Dubin model is established to test whether the opening of high-speed rail will reduce the air pollution level of surrounding cities through the spillover of industrial structure adjustment and technological progress.

Theoretical Analysis

The opening of high-speed rail has a direct impact on urban air pollution levels, mainly because the opening of high-speed rail accelerates the flow of population and capital factors among different regions, which are closely related to urban production activities and pollution emissions. Firstly, regarding the opening of high-speed rail and the flow of population factors, the free flow of population has an important impact on the optimization of labor allocation, economic development and environmental quality in China. The improvement of transportation infrastructure represented by high-speed rail reduces the cost of population mobility, improves the efficiency of population mobility, and expands the scale of population mobility. For the population inflow areas, the population inflow effectively improves the level of local human capital, which is conducive to improving the productivity of enterprises, promoting the innovation activities of enterprises, thereby reducing the pollution emission in the production process of enterprises and improving the urban air quality. However, for the places where the population flows, the large population inflow will increase the consumption of local resources and energy, and increase the emission of pollution in the atmosphere. At the same time, because China's overall population movement as a whole is characterized by low mass flow, and low quality of the population inflows tend to cause disorder agglomeration and low expansion, this leads to the local government in the process of urban infrastructure expansion, the urban land utilization drops, present a low quality, the phenomenon of sprawl, is not conducive to the improvement of the urban environmental quality. The expansion of urban population has increased the pressure on urban traffic and caused frequent traffic congestion. Traffic congestion leads to longer idle time of motor vehicles, which also increases exhaust emissions of motor vehicles and aggravates air pollution. Secondly, regarding the opening of high-speed rail and the flow of capital factors, the opening of urban high-speed rail has created more convenient conditions for the flow of capital, which is often accompanied by the production transfer and technology flow of enterprises. High-quality capital flows often lead to cleaner and more efficient industrial production technologies, which help local enterprises to produce cleaner and more energy efficient production activities, thereby reducing atmospheric pollution emissions and improving local air pollution. Low-quality capital flows tend to bring local heavy industrial enterprises with high pollution and high emission, which is conducive to local economic growth, but exacerbates local environmental pollution. Finally, open for high-speed rail and the configuration of resource factors, the development of high-speed rail to reduce the cost of elements flow elements and the flow range is bigger, faster, and promoted the relocation of resource factors, alleviate the factor allocation distortion degree, makes the elements to streamline configuration in production activities, to reduce the distortion due to elements of unreasonable consumption of resource factors, It is beneficial to improve enterprise productivity and reduce pollution emission. In conclusion, the opening of high-speed rail directly affects urban air quality by promoting factor flows, but the environmental effects of the opening of high-speed rail need to be tested in the empirical analysis below.

The opening of high-speed railway has created more convenient conditions for the flow of population and capital factors between regions, and unblocked the flow of factors between regions, thus having an important impact on technological progress. From the aspects of population flow, smooth flow of population elements make the configuration of the labor market role further optimization [8], promote the rational flow of the regional high-quality talent, high-quality talent usually have a lot of knowledge and technology, high-speed development flow of talent to promote the regional knowledge, technical communication, Thus, it is beneficial to produce learning effect and sharing effect. The talent flow caused by the opening of high-speed rail improves the level of local human capital, helps enterprises to carry out innovation activities, and promotes technological progress, thus promoting the development and application of clean and emission reduction technologies, and providing technical support for urban pollution reduction and haze reduction [16]. For labor-intensive enterprises in the secondary industry, the pressure from environmental regulations and labor costs will force them to engage in technological innovation and promote the upgrading of cleaner and more energy-efficient technologies to cut pollution emissions [23]. In terms of capital flow, the flow of high-quality capital among regions is often accompanied by the flow of advanced technologies. For local enterprises, the advanced technologies brought by high-quality capital are not only conducive to the improvement of enterprise productivity, but also conducive to the reduction of pollution emissions in production activities. Since enterprises need to invest a large amount of capital in production, research and development and innovation activities, capital inflow can improve the financial situation of enterprises, so that enterprises can invest more capital in production technology research and development and innovation activities, and promote technological progress. In addition, high-speed rail is an integration of new technologies. Thus, its production has higher technical requirements, which in turn has led to technological progress and structural optimization in the industrial chain related to high-speed rail, resulting in a reduction in the share of highly polluting enterprises in the whole industry [17].

The opening of HSR has increased the efficiency of factor mobility and optimized the allocation of resources. The acceleration of factor mobility promotes the adjustment of industrial structure in cities and allows for a more rationalized industrial layout. For example, the massive movement of people brought about by the opening of HSR has boosted the development of the city's tertiary industry, accelerating the expansion of service industries such as catering, tourism, and accommodation. The secondary industry is more dependent on natural resources and energy and is one of the main sources of pollution emissions in cities. The opening of HSR will prompt the city to phase out and relocate high-polluting and energy-intensive enterprises. The restructuring of urban industries has led to a decrease in the share of secondary industries and an increase in that of tertiary industries, which has reduced the dependence of urban industries on natural resources and energy. Pollution emissions in cities are reduced, contributing to the improvement of urban air quality [20]. The opening of HSR has changed the cost of enterprises, as it has directly raised the labor cost of enterprises by facilitating the mobility of labor factors and reducing transportation costs [21]. The increase in labor costs has eliminated the comparative advantage of labor-intensive and high-polluting companies from low labor costs, forcing them to shift from large cities to small and medium-sized cities. This industrial shift will reduce industrial emissions in large cities, although in turn increase pollution emissions in small and medium-sized cities. While big cities with a developed economy will be less willing to accept polluting enterprises after the opening of HSR, small and medium-sized cities with the less developed economy will be relatively more receptive to polluting enterprises [22]. Since economic growth is more important to some small and medium-sized cities than the prevention of environmental pollution, they are willing to take on polluting enterprises as a means of increasing local output level as well as the employment rate.

The opening of HSR can have a substitution effect on the original means of transportation. As a low low-carbon and low-consumption mode of transport, HSR has the advantages of comfort, convenience, accessibility, and large passenger capacity, and is more environmentally friendly compared to motor vehicles and airplanes. The opening of HSR reduces people's reliance on motor vehicles and airplanes for their travel, thereby reducing pollution emissions from roads and airlines [15]. Some scholars have studied the traffic substitution effect of the Seoul-Busan HSR line on air passengers and found that the opening of the HSR will reduce air passengers by 69.5% and 59.0% in Seoul-Busan and Seoul-Daegu respectively [24]. But it is also the convenience, accessibility, and relatively low travel costs of HSR that stimulate people to travel, increasing the demand for train frequency. As a result, more air pollutants are emitted.

In summary, the empirical analysis in this paper is mainly focused on the impact of the opening of HSR on industrial structure, technical level, and human capital level. The specific impact of the opening of HSR on urban air quality will be studied in this paper in the context of the substitution effect of HSR on the existing traffic passenger capacity. Based on previous studies, this paper investigates the heterogeneous impact of the opening of HSR on urban air quality from the reality of the new stage of high-quality economic development, combined with the medium- and long-term planning of HSR construction. The above study is conducted with a multi-period DID model. This paper also studies the inherent mechanism of the impact of the opening of HSR on air quality through mechanism test and establishment of spatial Durbin model.

Analysis Model

HSR service can be regarded as a quasi-natural experiment. As the operation time of HSRs differs by city, this study adopts the progressive DID method to evaluate the emission reduction effect of HSR operation. The basic model is specified as follows:

$$Y_{it} = \alpha_0 + \alpha_1 HSR_{it} + \beta X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where Y_{it} is the explained variable, denoting the air pollution level of the city i in year t, expressed as the value of $PM_{2.5}$ concentration. HSR is the kernel explanatory variable and its value equals du*dt, therein du is a dummy variable denoting the treatment group, which takes 1 if city i is in the treatment group where HSR has been deployed and 0 otherwise, dt is another dummy variable for the year of HSR operation, which takes 1 if HSRs are in service in year t and 0 otherwise. In general, the operation time of HSRs is based on the opening of the first HSR line in each city. As the operation time of HSRs differs by city, this study sets that if the HSR operates before 30 June of a given year, it is counted as an opening in that year, otherwise the opening is counted in the following year. The coefficient on the interaction term HSR indicates the difference in the impact of the opening of HSR on the treatment and control groups. X_{it} represents a series of control variables affecting the air quality, including the level of economic development (pgdp), expressed as real GDP per capita; environmental regulation (er), expressed as the ratio of SO_2 emissions to regional GDP; fiscal decentralization (fiscal), expressed as the ratio of fiscal revenue to fiscal expenditure; population density (pdensity); industrial structure (is), expressed as the share of tertiary output in regional GDP; R&D input (rd), expressed as the share of local budget expenditure on science and technology; transport infrastructure (road), expressed as per capita urban road area. μi and γt denote individual and time-fixed effects, respectively; and εit is the error term. The variable definitions and descriptive statistics are shown in Table 1.

Due to the absence or anomalies of relevant data and the redistribution of relevant administrative regions, this paper excludes data for the cities of Lhasa, Chaohu, Sansha, and Laiwu, of which Laiwu was merged into Jinan in January 2019 and is therefore excluded from the study. The final sample includes 278 cities in China from 2003 to 2019. The data for the dependent variable is obtained from the China City Statistical Yearbook 2004-2020, China Statistical Yearbook 2004-2020, China Urban Construction Statistical Yearbook 2020, the official websites of EPS DATA, the National Railways Bureau, and prefectural-level cities' government.

Empirical Analysis

Meet the parallel trend hypothesis is a prerequisite for using the DID method. Therefore, this paper uses the counterfactual test [18] and advances the opening of HSR by four years to test the validity of the parallel trend hypothesis and the dynamic effect of the opening of HSR on urban air quality. The model is specified as follows:

$$Y_{it} = \alpha_0 + \sum_{t=-4}^{9+} \varphi_t hsr_t + \beta X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

where hsr_t is the interaction term of the dummy variable for the opening time of HSR and the treatment group. Before the opening of the HSR, hsr = pre_t*du. And after the opening of the HSR, hsr = $post_t$*du. In Equation (2), hsr_{9+} denotes year 9 and beyond after the opening of the HSR and the remaining coefficients are consistent with Equation (1). In addition, the coefficient measures the impact on urban air quality in year t before (after) the opening of HSR, which is the key point of the parallel trend test. Fig. 2 shows the results of the counterfactual and dynamic effect tests for the impact of the opening of HSR on urban air pollution level. None of the dummy variable coefficients for the four years before the opening of the HSR passed the significance test, as it was determined that the model in this paper satisfied the parallel trend hypothesis.

Table 1. Descriptive statistics.

Variable	Definition	Obs.	Mean	S.D.	Min	Max
lnpoll	Air pollution level	4726	3.773	0.333	2.591	4.690
HSR	Whether high-speed railway is opened (1 if Yes, 0 otherwise)	4726	0.281	0.450	0	1
lnpgdp	Gross domestic product per capita	4726	10.221	0.836	4.595	13.056
lner	Environmental regulation	4726	3.407	1.579	-5.689	7.940
fiscal	Fiscal decentralisation	4726	0.481	0.225	0.055	1.541
lnpdensity	Population density	4726	5.740	0.896	1.547	7.923
is	Industrial structure	4726	0.386	0.095	0.086	0.836
rd	R&D input	4726	0.013	0.014	0.000	0.207
lnproad	Per capita urban road area	4726	0.963	0.949	-2.487	4.291

In this paper, a progressive DID model is developed to investigate whether the opening of HSR contributes to the improvement of urban air quality. The estimation results of the progressive DID model are shown in Table 2. It can be found that without the inclusion of control variables, the HSR coefficients are negative in both the fixed-effects regression model controlling for individual effects, i.e. model (1), and the two-way fixed-effects regression model controlling for year and individual effects, i.e. model (2). Therefore, it can be concluded that the opening of HSR can significantly reduce the concentration of PM2.5 in cities and improve urban air quality. With the inclusion of control variables, the results remain the same in the fixed-effects regression model and the two-way fixed-effects regression model, i.e. models (3) and (4), where the opening of HSR significantly reduces urban air pollution levels. The results of model (4) indicate that, in terms of the economic significance of HSR, cities with HSR have significantly lower PM2.5 concentrations by 1.7% compared to cities without HSR, controlling for other conditions.

Although endogeneity problems caused by individual differences in cities can be solved by the DID method, there will still be other similar problems because the construction plan of HSR, the cities where HSR will be constructed, and the location of the HSR stations are subject to government planning rather than being random variables events. Based on the relevant data of cities with HSR operations, it can be found that those with a more developed transport network and a higher level of economic development are more likely to have HSR construction programs and the implementation are often earlier. Therefore, we postulate that there are other factors that contribute to the endogeneity of the core explanatory variable, i.e. the opening of HSR, and lead to the inconsistency of estimated coefficients between the opening of the HSR and urban air quality. To address the endogeneity of relevant variables, this paper will use the instrumental variables approach for regression analysis. Referring to the method used by [16], the average slope of 278 cities is used as the instrumental variable. The average slope is a variable with geographical attributes, which is exogenous and can reflect the topographical features of a city. As the average slope of a city can affect the planning and construction costs of HSR lines, it could be considered to be relevant to the opening of HSR. And since it is a time-invariant variable, this paper uses an interaction term between the average slope and China's urbanization rate for each year as the instrumental variable for the opening of HSR. The results of instrumental variables regression are shown in Table 3. According to the results of the first stage regression, the likelihood of the opening of HSR is correlated with the instrumental variable at the 1 percent level of significance. The results of the second stage regression indicate that the opening of HSR has significantly reduced pollution levels in cities and improved urban air quality, which is in line with the findings of the basic regression analysis in the previous section.

To exclude the interference of policy shocks on random and residual variables, referring to the approach in the study by [25], this paper conducted a 500 replicate placebo test by randomly selecting the cities and years in which HSR operates. Fig. 3 shows the distribution of the kernel densities of the estimated coefficients after 500 replicate tests and the p-values. It is easy to see that the estimated coefficients derived from the random samples have mean values close to zero and most p-values are greater than 0.1. Furthermore, the actual estimated coefficients for the opening of HSR in the model (4) are outliers in Fig. 3. Accordingly, based on the above analysis, the environmental effect of the opening of HSR is not the result of conventional stochastic factors or unobservable factors.

The basic regression analysis in the previous section takes the value of PM2.5 concentration as a measure of urban air quality. To prevent inaccurate study results due to inappropriate selection of indicators, the following section will replace the PM2.5 indicator

Table 2. Results of Basic Regression Analysis

	(1)	(2)	(3)	(4)
HSR	-0.165***	-0.023***	-0.041***	-0.017***
	(0.005)	(0.004)	(0.005)	(0.004)
lnpgdp			0.039***	-0.028***
			(0.006)	(0.007)
lner			0.046***	0.003*
			(0.002)	(0.002)
fiscal			0.046**	-0.071***
			(0.020)	(0.018)
lnpdensity			0.021	-0.130***
			(0.033)	(0.027)
is			-0.747***	-0.084**
			(0.039)	(0.036)
rd			0.287**	-0.742***
			(0.146)	(0.138)
lnproad			-0.026***	-0.008*
			(0.006)	(0.004)
_cons	3.820***	3.780***	3.394***	4.878***
	(0.002)	(0.001)	(0.186)	(0.170)
Control variables	No	No	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	No	Yes	No	Yes
N	4726	4726	4726	4726
adj.R-sq	0.873	0.951	0.917	0.952

Note: Above the parentheses are the estimated coefficients for each variable. The standard errors are in parentheses. *,** and *** indicate statistical significance at the 10%, 5% and 1% levels.

Table 3. Results of Instrumental Variables Regression.

	Stage 1	Stage 2
Dependent variable	HSR	lnpoll
HSR		-0.747***
		(0.296)
iv	0.123***	
	(0.048)	
Control variables	Yes	Yes
Individual fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	4726	4726
adj.R-sq	0.611	0.574

with industrial wastewater effluent (sewage) and log the value before doing the calculation. In addition, as the opening of HSR is the core explanatory variable in this paper, and given that there are different ways of measurement for this variable, a further robustness test of the findings that the opening of HSR can improve urban air quality will be conducted here with the number of HSR stations in the city. Considering that municipalities and provincial capitals have their unique political, economic, and geographical advantages over other prefecture-level cities, there is a large gap in terms of comprehensive strength between these cities. Therefore, it is necessary to exclude municipalities and provincial capitals and adjust the city samples for the regression analysis. In addition, China is a vast country with significant geographical differences and economic development levels among different regions, thus the construction of HSR is not entirely the event of a random variable. To avoid errors in the results arising

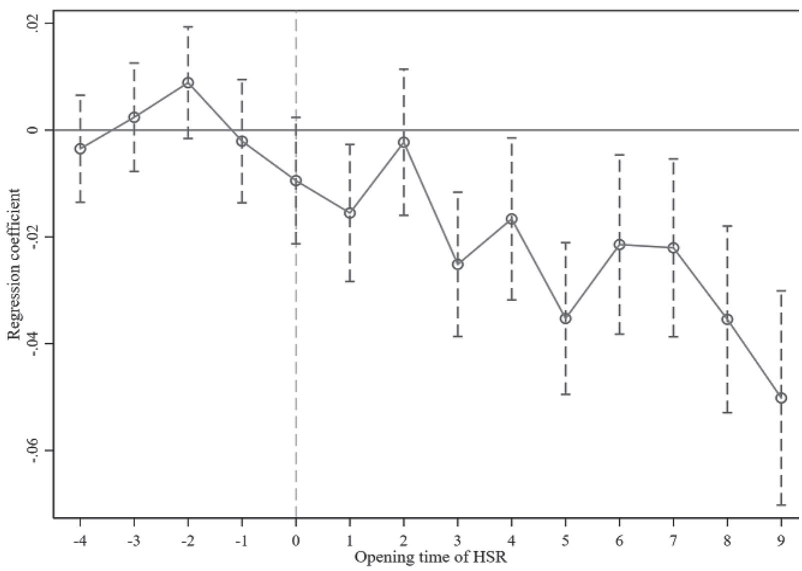

Fig. 3. Results of Parallel Trend Test.

from sample selection bias, this paper uses the PSM-DID approach for the robustness test.

According to Table 4, the coefficients of HSR in the models (1), (3), and (4) are still significantly negative after the robustness tests of replacing the explained variables, excluding the municipalities and provincial capitals, and conducting PSM-DID. And after replacing the core explanatory variables, the coefficient of the number of HSR stations in the model (2) is also significantly negative. Therefore, as the estimated coefficient results of the models (1), (2), (3), and (4) are all consistent with previous findings, it can be concluded that the findings in the basic regression analysis are robust, the opening of HSR can bring about environmental effects of improving urban air quality.

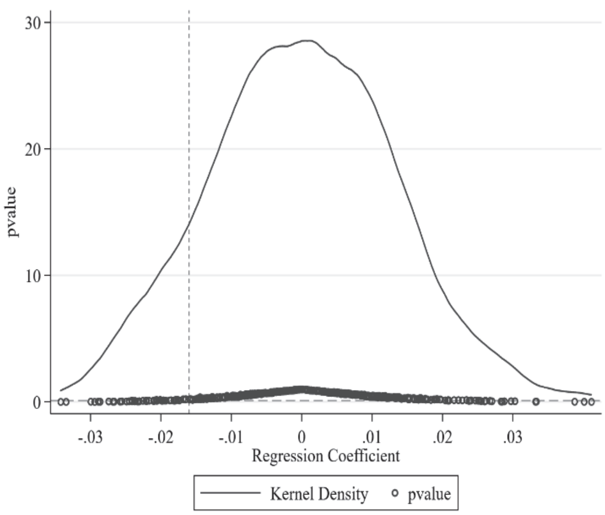

Fig. 4. Distribution of the Kernel Densities.

Heterogeneity Analysis

China is a vast country with marked differences in economy, culture, geography, and climate between different regions, so it is necessary to analyze the heterogeneous impact of the opening of HSR on urban air quality on a regional basis. This paper divides the 278 cities in China into two parts belonging to the south and the north respectively according to the provincial administrative area. The two have major differences in climate, industrial structure, and people's living habits. For example, there are more heavy industries and high-polluting enterprises in the north than in the south. And provinces in the north are centrally heated in winter, which relies heavily on coal. In general, haze pollution is a more serious problem in northern cities than in the south, which is of practical relevance to studying the heterogeneous impact of the opening of HSR on urban air quality by dividing China's cities into of the north and the south. According to the results in Table 5, the opening of HSR significantly reduces the air pollution levels in southern cities, however, it fails to effectively reduce air pollution levels in northern cities, where air quality is worse. The opening of HSR has little effect on the improvement of urban air quality. This paper thinks that there are the following possible reasons: Since the reform and opening up, the degree of opening up of the southern cities is generally superior to that of the northern cities, and the level of economic development is generally higher than that of the northern cities. Therefore, compared with northern cities, southern cities are more attractive to talents, capital and other factors, and also bring more emerging industries and high and new technologies. However, northern cities have relatively more heavy industry enterprises with high pollution, high emission and high energy consumption, the development level of

Table 4. Results of Robustness Test.

	Replacing the explained variables	Replacing the core explanatory variables	Excluding the municipalities and provincial capitals	PSM-DID
	(1) lnsewage	(2) lnpoll	(3) lnpoll	(4) lnpoll
HSR	-0.128***		-0.023***	-0.016***
	(0.025)		(0.004)	(0.004)
Station		-0.005***		
		(0.001)		
Control variables	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
N	4726	4726	4216	4544
adj.R-sq	0.840	0.952	0.953	0.953

private economy is lower than that of southern cities, and the lack of innovation impetus makes it difficult to research and promote energy-saving and clean production technologies. Industrial upgrading resistance is greater. This is why the opening of high-speed rail has a heterogeneous impact on southern and northern cities. Therefore, accelerating industrial upgrading in northern parts of China, reducing high-polluting enterprises, and promoting the application of cleaner heating technologies are effective ways to reduce urban haze pollution.

Regarding the criteria and results for assessing cities in China published by the China Business Network, this paper defines 1st-tier cities and new 1st-tier cities as major cities, 2nd-tier cities as bigger cities, and 3rd-tier cities and 4th-tier cities as mid-sized cities. In the heterogeneity analysis, the 2nd-tier cities, 3rd-tier cities, and 4th-tier cities are collectively defined as one category of bigger and mid-sized cities for the regression analysis, while 5th-tier cities are defined as small cities. Such classification will facilitate the study of the heterogeneous impact of the opening of HSR on air quality in cities of different scales and economic development levels. Based on the results in Table 6, we find that the opening of HSR has significantly reduced the air pollution levels in major, bigger, and mid-sized cities and improved the air quality levels in these cities. For smaller cities, however, the effect failed the significance test. It can be deduced that the larger the city, the greater the effect. This may be a result of the fact that larger cities are more economically developed and have a relatively greater ability to gather talent, technology, capital, and other elements. The opening of HSR has further accelerated the flow of these elements, promoted technological progress, and improved the eco-friendliness of enterprises, thus reducing the overall urban pollution level. For smaller cities, the environmental effects of the opening of HSR are not significant as it strengthens the siphoning effect of the relatively larger cities on smaller ones.

Table 5. Results of heterogeneity analysis of cities in different regions.

	Northern cities	Southern cities
HSR	0.003	-0.014***
	(0.006)	(0.005)
Control variables	Yes	Yes
Individual fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	2159	2567
adj.R-sq	0.955	0.961

Mechanism Examination

According to the previous theoretical analysis, this paper holds that there are two main ways for the opening of HSR to affect urban air quality.

Table 6. Results of heterogeneity analysis of cities in different scales.

	Major cities	Bigger and mid-sized cities	Small cities
HSR	-0.032**	-0.016***	-0.012
	(0.015)	(0.005)	(0.009)
Control variables	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	323	3026	1377
adj.R-sq	0.940	0.960	0.931

Table 7. Results of traffic substitution effect.

	Road passenger transport capacity	Civil aviation passenger transport capacity
HSR	0.015	-0.210***
	(0.026)	(0.052)
Control variables	Yes	Yes
Individual fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	4725	2054
adj.R-sq	0.766	0.917

Firstly, This paper focuses on the substitution effect of the opening of HSR on road and air passengers. The regression results in Table 7 show that the substitution effect of the opening of high-speed rail on road passenger transport capacity shows no significance, while the test for civil aviation passenger transport capacity passes the significance test. The opening of HSR has significantly reduced the number of people who opt to travel by air. The possible reason for this is that before the opening of HSR, people's first choice for short trips was generally road transportation, while for mid- and long-distance trips, people's choice was normally train or plane. The opening of HSR has provided people with a new option for travel, but since most cities have HSR stations built far from the city center, taking accessibility into account and weighing up the cost of transportation and time, people's choices differ: For short trips, high-speed rail cannot capture its convenience, thus the substitution effect on road transportation is not significant. While for mid- and long-distance trips, high-speed rail is safer and more convenient than air travel and the overall cost is lower, thus the substitution effect on civil aviation transport is much more significant.

Secondly, according to the above theoretical analysis, high-speed rail can affect urban air quality by promoting industrial structure upgrading and technological progress. In this paper, the industrial structure advanced index is used to represent the industrial structure, and the number of patents is used to represent the technological progress. The index of industrial advancement is an important indicator of the transformation and upgrading of industrial structures. The larger the proportion of the tertiary industry output values, the higher the tertiarization is in the city. Referring to the study by [18], the index is used in this paper to indicate the advancement of industry in cities and the formula is as follows: $advance = 1 \times s1 + 2 \times s2 + 3 \times s3$, where s1, s2, s3 respectively represent the share of primary, secondary and tertiary output in regional GDP. The index of industrial rationalization can reflect

Table 8. Results of mechanism test.

	lnpoll	lntech	Advance
HSR	-0.017***	0.056***	0.006***
	(0.004)	(0.020)	(0.002)
Control variables	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	4726	4726	4726
adj.R-sq	0.952	0.957	0.916

the dynamic process of continuous improvement in inter-industry coordination and association [26]. The higher the level of industrial rationalization in a city, the more successful the transformation and upgrading of the city's industrial structure. The industrial layout is thus more reasonably arranged.

According to the results of the regression analysis shown in Table 8, the opening of high-speed rail has significantly improved the level of urban industrial upgrading and innovation, and promoted the adjustment of urban industrial structure and technological progress. In terms of industrial structure adjustment, the flow of factors brought about by the opening of high-speed rail promoted the development of the tertiary industry in the city, and prompted the city to phase out and transfer the enterprises with high pollution and energy consumption in the secondary industry. Therefore, the opening of high-speed rail reduced the proportion of the secondary industry, increased the proportion of the tertiary industry, reduced pollution emissions in production activities, and improved the urban air quality. In terms of technological progress, the opening of high-speed rail has provided talents and capital for innovative activities of local enterprises, promoted the clean production technology of enterprises, and reduced pollution emissions in the production process.

Finally, this paper uses a spatial econometric approach to analyze the spillover effects arising from the opening of HSR, mainly examining whether the opening of HSR will reduce air pollution levels in neighboring cities through the spillover effect of technological progress and industrial structure upgrading. Before conducting the spatial econometric analysis, this paper first structures an inverse economic distance spatial weight matrix and performs a spatial autocorrelation test on the study variables. As shown in Table 9, this paper calculates the Moran's I index for indicators of urban lnpoll, lntech, and advance under the inverse economic distance spatial weight matrix. All Moran's I indices are significantly positive, indicating that urban pollution emissions, technological progress, and industrial structure upgrading are characterized by significant spatial agglomeration

Table 9. The test of spatial autocorrelation.

	Moran's I		
	lnpoll	lntech	Advance
2003	0.708***	0.376***	0.124***
2004	0.675***	0.390***	0.130***
2005	0.722***	0.394***	0.157***
2006	0.705***	0.408***	0.152***
2007	0.708***	0.409***	0.172***
2008	0.672***	0.402***	0.184***
2009	0.701***	0.430***	0.213***
2010	0.700***	0.455***	0.215***
2011	0.666***	0.482***	0.234***
2012	0.678***	0.490***	0.242***
2013	0.674***	0.493***	0.250***
2014	0.654***	0.509***	0.253***
2015	0.707***	0.518***	0.270***
2016	0.697***	0.509***	0.247***
2017	0.647***	0.500***	0.236***
2018	0.661***	0.521***	0.223***
2019	0.680***	0.527***	0.220***

[27]. In addition, after conducting the Hausman test, LR test, and Wald test, the SDM model with space-time fixed is established for the spatial regression analysis in this paper. According to the results in Table 10, the spillover effect of the opening of HSR has significantly reduced pollution emissions from surrounding cities and contributed to the improvement of air quality in these cities. The opening of HSR has stimulated the flow of technological elements and the restructuring of industries. While the spillover effect from technological progress and industrial structure upgrading has also dramatically reduced the pollution levels in surrounding cities, producing a good environmental effect. Therefore, based on the above results, this paper concludes that the flow of talent, knowledge, capital, and other elements between cities has increased following the opening of HSR. The spillover effect from HSR has promoted technological progress in local and neighboring cities and has also accelerated the pace of urban industrial restructuring, which has led to the advancement of cities' industrial structure and thus reduced the city's $PM_{2.5}$ emissions.

Table 10. The test of the spillover effect.

	lnpoll		
	Direct Effect	Indirect Effect	Total Effect
HSR	-0.004	-0.065***	-0.068***
	(0.003)	(0.022)	(0.024)
lntech	-0.001	-0.032**	-0.034**
	(0.002)	(0.013)	(0.014)
Advance	-0.008	-0.341**	-0.349**
	(0.020)	(0.136)	(0.148)

Conclusions and Suggestions

Based on the panel data of 278 cities in China from 2003 to 2019, this paper makes an empirical study on the influence of high-speed rail on city-level air quality by using the opening of high-speed rail as a quasi-natural experiment and taking the method of progressive DID estimation model. And heterogeneity analysis is conducted for cities of different sizes and geographic regions. Furthermore, the paper examines the mechanism of the impact of HSR on urban air quality in terms of promoting technological progress and industrial structure upgrading and generating substitution effects. The main findings of this paper are as follows: 1) The opening of high-speed rail significantly improves city-level air quality, and the conclusions are still valid after a series of robustness tests and dealing with endogenous problems. 2) According to the heterogeneity analysis, the opening of high-speed rail in southern cities significantly reduced air pollution levels, while the environmental effects in northern cities failed the significance test. 3) For the analysis of cities of different scales, the haze reduction effect of the opening of HSR is significant for mid-sized and larger cities. While for smaller cities, the opening of HSR doesn't have a notable impact on air quality improvement. 4) The substitution effect of the opening of high-speed rail on civil aviation transport passes the significance test, while the test for highway passenger transport shows no significance. 5) The test of mechanism and spatial spillover effect shows that the opening of HSR can promote technological progress and accelerate the upgrading of industrial structures, as well as reduce air pollution levels in neighboring cities through the spillover effect.

According to the findings of this paper, the following suggestions are made: 1) Since the opening of HSR can significantly reduce the $PM_{2.5}$ concentration in urban air and improve air quality, the Chinese government should continue to vigorously promote the construction of HSR to achieve the goal of building the "eight horizontal and eight vertical" high-speed railway network. China should strive to achieve the plan of connecting internal and external HSR routes, providing smooth inter-regional access to multiple routes, connecting provincial capitals via HSR, providing fast access to cities and towns, and covering countries largely with HSR routes. 2) The government should proactively promote the application of cleaner heating technologies in cities in the northern provinces to reduce reliance on coal and thus achieve haze reduction. Compared to cities in the southern provinces, cities in northern provinces are home to more heavy industries and high-polluting enterprises. Therefore, technological upgrading should be achieved as soon as possible for completing the upgrading of industrial structure is an effective way to reduce urban air pollution levels. 3) It is important to give priority to the construction of HSR in medium-sized and larger cities and to build a denser and more reasonable HSR network to include more cities in the HSR system. For smaller cities, it is important not to blindly build HSR routes, but to plan the railway construction with a longer-term perspective. Overall, the number of HSR miles should not be overly pursued, instead, the planning and design of HSR routes should be given more attention. It is important to maximize the utilization of each HSR line so that it can encompass more cities and thus provide a wider impact on the environmental effects of the opening of HSR. 4) For daily travel, people should reduce their reliance on airplanes and other high-emission means of transportation, and choose to travel by HSR. Due to the relatively remote location and inconvenient access to some HSR stations in cities, the related infrastructure needs to be further improved so as to enhance the convenience of HSR rides. 5) City's industrial development planning should be more scientific and environmentally friendly. In the new stage of high-quality development, cities that have built HSR should make full use of the advantages of HSR and grasp the talents and other resources brought about through the spillover effect. Actively promoting technological progress and upgrading the industrial structure can lead to a more efficient urban industrial structure.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. ZHANG H., FENG Y. Green high-speed rail: Can haze pollution be reduced by the running of high-speed rail? Journal of Economics, **6** (3), 114, **2019**.
2. WANG Q., ZHANG D.W., LIU B.X., CHEN T., WEI Q., LI J.X., LIANG Y.P. The spatial and temporal distribution characteristics of PM2. 5 resources from Beijing based on the PMF module. China Environmental Science, **15** (10), 2917, **2015**.
3. LIANG R.B., XI P. H. The heterogeneous influence of air pollution caused by rail traffic – an empirical research based on RDID method. China Industrial Economy, **16** (3), 83, **2016**.
4. GAO M., CHEN L.Q., GUO S.H. Rail traffic, BRT and air quality – a view of urban heterogeneity. China Population, Resources and Environment, **28** (6), 73, **2018**.
5. HE X.J., LIAO S.W., ZHAO Z.X. The impact of atmospheric environment caused by urban electric vehicle's scale development. Chinese Journal of Environmental Management, **12** (3), 77, **2020**.
6. KIM H.W., LEE D.H., PARK H.S. The impact of Gyeongbu high-speed rail construction on regional economic growth. Ksce Journal of Civil Engineering, **17** (6), 1206, **2013**.
7. WANG Y.F., NI P.F. The economic growth spillover and regional spatial optimization under the impact of high-speed rail. China Industrial Economy, (2), 21, **2016**.
8. ZHAO X., LIU J. Research on technological progress effect of high-speed railway opening. Modern Economic Discussion, (05), 92, **2021**.
9. BIAN Y.C., WU L.H., BAI J.H. Does High-speed-Rail Improve Regional Innovation in China? Journal of Finance Research, (06), 132, **2019**.
10. WEN Y.B., ZHANG M.T., YU F. A Study on the Resource Reallocation Effect of China's Transportation Infrastructure. Economic Research Journal, **57** (01), 155, **2022**.
11. LI S., ZHU W.P., LIU D. Whether high-speed railway can promote the upgrading of industrial structure: Based on the perspective of resource reallocation. South China Economy, (02), 56, **2020**.
12. SUN W.Z., NIU D.X., WAN G.H. Transportation Infrastructure and Industrial Structure Upgrading: Evidence from China's High-speed Railway. Management World, **38** (03), 19-34+58+35-41, **2022**.
13. CHIPINDULA J., DU H., BOTLAGUDURU V.S.V. Life cycle environmental impact of a high-speed rail system in the Houston-Dallas I-45 corridor. Public Transport, **14**, 481, **2022**.
14. HEATHER J., FILIPE M., TIAGO D. Life cycle assessment of high-speed rail: A case study in Portugal. The International Journal of Life Cycle Assessment, **17** (22), 410, **2017**.
15. FAN J.S., ZHOU L., YU X.F. The heterogeneous influence from high-speed rail and urban sprawl. Geographical Research, **40** (4), 1146, **2021**.
16. WANG Q.Y., LU F.Z. The economic effect of the opening of high-speed rail: Emission reduction and improve efficiency. Statistical Research, **38** (2), 29, **2021**.
17. ZHANG M.Z., YU D.H., SUN T. The impact of urban production system's green reconstruction from the opening of high-speed rail. China Population, Resources and Environment, **29** (7), 41, **2019**.
18. LI J.M., LUO N.S. Have the condition of urban air pollution been improved by the opening of high-speed rail? China Economics Quarterly, **19** (4), 1335, **2020**.
19. QIN Z.L., CHEN X.G. Have the urban air quality along the railway been improved by the opening of high-speed rail – Based on the analysis of breakpoint regression design. Journal of Environmental Economics, **5** (2), 76, **2020**.

20. ZHANG B.R., LI Z.J. Can high-speed rail improve low carbon economy – The impact and system research of urban carbon emission intensity from the opening of high-speed rail. Journal of Huazhong University of Science and Technology, **35** (1), 131, **2021**.
21. DONG Y.M., ZHU Y.M. Whether Chinese economic spatial layout can be reconstructed by the construction of high-speed rail – Based on the regional heterogeneous views of employment, salary and economic growth. China Industrial Economy, **16** (10), 92, **2016**.
22. CAI H.B., ZHONG C., HAN J.R. The improvement of transportation infrastructures and the site selection of polluting enterprises. China Industrial Economy, **21** (10), 136, **2021**.
23. SUN P.B., GE L.M. The way to low carbon: the impact of industrial carbon emission from the opening of high-speed rail. The Journal of World Economy, **44** (10), 201, **2021**.
24. KIM, K.W., SEO, H.Y., KIM, Y. Forecast of domestic air travel demand change by opening the high speed rail. KSCE Journal of Civil Engineering **7** (5), 603, **2003**.
25. CAI X., LU Y., WU M. Does environmental regulation drive away inbound foreign direct investment? evidence from a quasi-natural experiment in China. Journal of development economics, **123**, 73, **2016**.
26. YUAN H., ZHU C.L. Do national high-tech zones promote the transformation and upgrading of China's industrial structure? China Industrial Economy, **18** (8), 60, **2018**.
27. WANG K.L., PANG S.Q., ZHANG F.Q. Can the opening of high-speed rail improve urban green total factor productivity? Industrial Economic Research, **21** (03), 112, **2021**.