Management System Engineering

RESEARCH ARTICLE Open Access

The impact of high-speed railway construction on regional economic development in Hubei Province

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Abstract

Based on the panel data of 16 cities in Hubei Province from 2009 to 2019 (excluding the data during Covid-19 pandemic period), we construct multi-temporal difference-in-differences model (DID) and Spatial Durbin model (SDM) to explore the impact of the High-speed Railway (HSR) construction on the regional economic development in terms of direct economic effect, indirect economic effect and spatial spillover effect. The main conclusions of this paper are as follows: firstly, HSR construction promotes the economic development of cities in Hubei Province in a long time and in a large spatial scope. And the impacts on the economic development are significantly heterogeneous among different types of cities. Also, HSR construction has widened the economic development gap among cities to some extent. Secondly, the upgrading of an industrial structure and the improvement of urbanization level both play mediating roles in the economic impact of HSR construction. Thirdly, the HSR construction has significant spatial spillover effect on economic development, but the spillover effect becomes insignificant with the increase of distance.

Keywords Multi-temporal difference-in-differences model, Spatial Durbin model, Spatial spillover effect, Mediation effect

1 Introduction

The high-speed railway (HSR) in China has been developing rapidly during recent years. The Annual Railway Statistics Report shows that the length of HSR in service has reached 42,000 km until 2022. From 0 to 42,000 km, the HSR lines have become a network, specifically a "eight vertical and eight horizontal" network. The construction of HSR has greatly shortened the distance among cities in terms of time and space, and has brought closer economic ties among cities along the line and promoted regional economic development. Therefore, this paper aims to analyze the impacts of HSR on the economic development through building multi-temporal difference-in-differences (DID) model and Spatial Durbin model (SDM).

As an efficient bridge connecting different cities, HSR operation can accelerate the flow of talents, resources, capital and other elements, and may further impact the regional economic development. Regarding the impacts of HSR, scholars hold different views. Some scholars believe the HSR operation may lead to polarized development, while other scholars argue it may promote balanced and consistent development of all cities. In addition, some scholars propose that HSR not only promotes the local economic development, but also boost the development of surrounding cities. Accordingly, it raises some interesting questions: does HSR construction has a significant impact on the economic development? Does the introduction of HSR narrow

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or widen the economic gap among cities? How does HSR impact the local economic development? Does the HSR construction generate a spatial spillover effect on neighboring cities. The answers to these questions have long-term implications for urban development and HSR investment planning.

This paper chooses Hubei Province as the object of this study. Hubei Province, as one of the first provinces to open HSR, has the geographical advantage of being the center of the country's "eight vertical and eight horizontal" transportation corridor. The Wuhan-Yichang Railway and Shijiazhuang-Wuhan Railway have been completed and opened, the Shanghai-Wuhan-Chengdu Railway and the Beijing-Guangzhou Railway run through the province, and four intercity railways including Wu-Xian, Wu-Huang, Wu-Gang and Han-Xiao in Wuhan metropolitan area have been put into operation. The "cross-shaped" HSR network with Wuhan as the center and the radial Wuhan metropolitan area intercity network pattern have basically taken shape.

Although the railway construction in Hubei Province has made great progress, there are still some problems in the infrastructure, operation management and functional role. At present, the station capacity, river crossing channel, train configuration and equipment configuration of Wuhan rail transit hub could not meet the development needs of Wuhan, and it is difficult to realize fast and efficient interconnection with the new project construction in the whole country. Some cities and states open HSR speed is slow, the railway connection is not smooth, Wuhan metropolitan area, Xiangshisui metropolitan area, Yijing metropolitan area and the metropolitan area within the urban rail line connection is relatively simple. Xiangyang and Yichang, as provincial sub-centers, have a weak role as transportation hubs and do not give full play to their radiating power to the region. The construction of HSR has an important impact on the regional economic development of Hubei Province. At the same time, the construction of HSR in Hubei Province is currently in a period of vigorous development, so it is of typical and practical significance as a case study. From the regional level, it is expected to provide reference for the policy effect evaluation in this region and other regions.

The remainder of the paper is organized as follows. Section 2 introduces the literature review of existing research. Then, the multi-temporal difference-in-differences (DID) model and Spatial Durbin model (SDM) are proposed in Sect. 3, as well as the data processing and model robustness test. Furtherly, Sect. 4 applies the data of Hubei Province to explicate the impact of HSR construction on regional economic development level in terms of direct economic effect, indirect economic effect and spatial spillover effect. Finally, conclusions and further studies are presented in Sect. 5.

2 Literature review

Transportation development has two different effects on regional economic development: one is the growth effect and the other is the structural effect (Wang and Ni 2016). The growth effect is that the development of transportation promotes regional economic spillover, thus promoting economic growth (Yu 2022). While the structural effect is that transportation development changes the economic spatial pattern of regions (Wang et al. 2022). Many scholars believe that HSR networks directly promotes the economic development of cities by improving accessibility and narrowing the distance among cities economically (Xu et al. 2018; Liang et al. 2020; Zhou et al. 2021; Wang et al. 2023). Albalate and Bel (2012) found that U.S. HSR projects can enhance economic linkages among cities, thereby boosting economic development in cities along the route. With regard to the role of HSR networks in re-configuring the regional spatial patterns, scholars pay attention to the impact of HSR construction and development on regional development integration (Zhao and Wu 2020; He and Tao 2020). In Europe, evidence from Spain, France and the UK suggest that HSR has played an important role in facilitating intra-regional integration over distances of up to 200 km (Garmendia et al. 2012). Zhao et al. (2021) proposed that there is a two-way feedback mechanism between the HSR network and the regional economic linkage network by constructing the HSR hub construction model under big data.

The construction, operation and development of HSR not only improve the layout of the existing transportation network, but also accelerate the flow of talents, resources, capital and other elements (Yena et al. 2012). Besides, HSR construction works to optimize the allocation of resources, promote the upgrading of industrial structure (Luo et al. 2020; Zhang et al. 2022; Sun et al. 2022), improve the level of urbanization level (Qin et al. 2014; Ren et al. 2020), and then have a comprehensive effect on regional economic development. In addition to the direct impact on economic development, the construction of HSR networks has also has a major impact on economic activities along the line. Alañón-Pardo et al. (2013) studied the location decisions of Spanish manufacturing enterprises and found that agglomeration economies and accessibility play an important role in industrial location decisions. By using social network analysis method and spatial econometric model, Wang et al. (2022) found that the continuous improvement of the HSR network promoted the adjustment of local industrial structure, and its spillover effect promoted the adjustment of overall industrial structure. Li et al. (2022) analyzed the impact of the opening of HSR on the quality level of new urbanization in cities along the line based on the multi-temporal DID model. The results showed that the construction of HSR has promoted the high-quality development of new urbanization.

Urban traffic construction not only plays an important role in the development of the city itself, but also has a certain spatial spillover effect on the surrounding areas. The general forms of HSR spillover effects include economic spillover (Lu et al. 2022), knowledge spillover (He et al. 2020), and technology spillover (Xu et al. 2022). Hu et al. (2015) found that different levels of transportation hubs have a significant positive effect on the economic output of this region and its surrounding areas, and the spatial spillover effects of transportation hubs in the eastern, central and western regions are significantly different. Li et al. (2019) analyzed the impact of HSR on regional innovation, and found that both geographical distance and time distance have a significant impact on the spatial spillover effect of innovation. In spite of such positive impacts on economic growth, HSR may still bring about some negative externalities. According to the viewpoint of new economic geography theory, the improvement of the infrastructure construction level in a region may make the elements of the surrounding areas concentrate in the central area, thus slowing down the economic development of the surrounding areas, which is called the siphon effect (Lin 2017; Charles 2018; Zhao et al. 2021). For example, the opening of the Tokaido Shinkansen Line has further strengthened the geographical advantage of Tokyo. At the meanwhile, resources and talents from neighboring cities flow into Tokyo, showing an obvious concentration trend and giving rise to the siphon effect (Noboru and By 2011). The same case occurs with the opening of the HSR between Perpignan and Barcelona, which further enhances Barcelona due to its superior geographical advantage and tourism resource endowment (Masson et al. 2009). Zhang et al. (2022) also pointed out that the surrounding areas are easily affected by the siphon effect of central city and can hardly benefit from the spillover effect, which restrict the development of regional economy and thus produces the agglomeration shadow. As such, both the positive and negative impacts should be taken into account while planning the HSR network.

Prior studies have not reached a consensus whether HSR can promote regional economic growth. Some scholars believe that HSR may be a catalyst for economic growth, but it is not the main driving force, especially for areas far away from major metropolitan centers (Vickerman 2015; Baum-Snow et al. 2020). Guo et al. (2020) used the nighttime lighting data from 2002 to 2018, and found that the construction of Jingguang HSR had a very positive impact on the economy of new first-tier cities, but it damaged some second-tier cities and third-tier cities. Li et al. (2016) found that HSR is a derivative demand of economic growth, and its impact on economic growth will gradually weaken over time. In a certain period, HSR is only a basic background condition of economic development, and its impact on economic growth is not obvious. Wang et al. (2020) proposed that the opening of HSR will not promote the economic development along the line in a short time, but it will accelerate the economic diffusion along the line in the long run. To sum up, we find that the effect of HSR is characterized by time accumulation, heterogeneity and universality. Therefore, we should consider both advantages and disadvantages of HSR construction according to these characteristics, and take full advantage of HSR. Because the construction period of HSR is much shorter than the operation period, there is a time lag when HSR shows an impact on the regional economy. The impacts, such as improvement of the overall transportation system, acceleration of production factors flow and promotion of industrial structure may gradually appear a certain time after the HSR opening. Also, HSR has different impacts on different regions, such as central cities and surrounding cities. In addition, HSR can not only stimulate domestic demand and improve regional accessibility in the short term, but also promote the upgrading and optimization of regional economy and industrial structure in the long term. Therefore, the development of HSR has a very important impact on the development level of regional economy.

Although there is a broad literature on the analysis towards the impacts of HSR construction, some new jobs can still be done to complete this topic. Firstly, most of the research mainly reveals the impact of HSR construction on regional economic development based on a specific time without considering the dynamic impacts of HSR construction in long time series. Secondly, most of the existing studies mainly focuses on the national HSR network or a certain HSR line, lacking analysis of HSR service in a certain region. And it is difficult to reflect the impact mechanism of the HSR construction in specific areas. Accordingly, applying the panel data from 2009 to 2019 excluding the data during Covid-19 pandemic period, we construct a multi-temporal difference-in-differences (DID) model and a Spatial Durbin model (SDM). Based on the proposed models, the impact of HSR construction on the regional economic development is discussed from three aspects: direct economic effect, indirect economic effect and spatial spillover effect. And some corresponding suggestions regarding HSR construction are put forward in the end.

3 Model hypothesis

There are both consensus and different opinions regarding the impact of HSR on regional economic development. Generally, most scholars believe that the accessibility of HSR has produced a time–space compression effect, thus promoting the flow of elements in space and affecting the economic development of the city. The accumulation of these effects has also led to changes in the urban spatial structure, even though these changes are not balanced in space. But the main divergence of opinion among scholars lies in whether HSR construction leads to the polarized development or balanced development of urban agglomerations. Some scholars believe that HSR construction will gather population, logistics, capital and technology into central cities. And the development advantages of central cities will be further strengthened, while the surrounding areas will be weakened and the gap between cities will be widened. Some scholars also believe that HSR construction promotes the radiation effect of central cities to surrounding areas, and bringing the surrounding underdeveloped cities into the development pattern of central cities is of great significance to promoting the balanced development of space among cities. Therefore, how to scientifically and accurately evaluate the impact of HSR construction on the level of regional economic development is of great significance. According to the above research, this paper puts forward the following hypotheses:

H_{1a}: HSR construction has a positive relationship with regional economic growth.
H_{1b}: HSR construction has a temporal accumulation effect.
H_{1c}: HSR construction has widened the gap of regional economic development among cities to some extent.
H_{2a}: HSR construction has a mediation effect. And HSR construction has a significant promotion relationship with the upgrading of industrial structure, which in turn promotes the regional economic development.
H_{2b}: HSR construction has a mediation effect. And HSR construction has a significant promotion relationship with urbanization level, which in turn promotes the regional economic development.
H_3: HSR construction has a spatial spillover effect.

4 The construction of multi-temporal DID model

This paper focuses on the effects of HSR construction on the economic development of Hubei Province. Besides HSR, there are actually many other factors that may affect the regional economic growth. For example, the new urbanization construction promotes the economic development. Considering this, we proposed the Difference-in-difference model to evaluate the effects of HSR construction, which is often used to evaluate the effect of policy implementation. The method examines the differences of cities with and without HSR, before and after the opening of HSR. The two-level comparison can more reliably determine the impact of HSR opening on economic development, minimizing interference from other influencing factors as much as possible. This ensures the results predominantly reflect the actual impact of HSR.

We propose a multi-temporal DID model to analyze the impact of HSR opening construction on regional economic development. According to the implementation of the HSR opening policy in Hubei Province, we divide cities into the treated group and the control group. The cities with HSR are listed as the treated group, and the cities without HSR are listed as the control group. We judge the impact of HSR operation by comparing the differences of various indexes between the treated group and the control group before and after the opening of HSR.

4.1 Direct economic effect analysis of HSR construction

(1) Direct effect of HSR on economic development level

Denote HSR_{it} as a binary variable for HSR opening, which equals 1 when the HSR is opened in city i at year t and equals 0 otherwise. This variable is the core explanatory variable of this paper and the actual policy effect of the opening of HSR. The multi- temporal DID model is as follows:

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where i and t denote the city i and the year t. Y_{it} is the dependent variable, using the nighttime lighting data to represent the economic growth index. HSR_{it} is a virtual variable for HSR opening. X_{it} is a set of control variables, including the level of labor concentration, market size, capital investment, infrastructure construction level, science and technology investment, enterprise competitiveness and education quality level. μ_i represents the individual fixed effect of each city, reflecting the individual heterogeneity effect that affects economic growth. γ_t represents the time solid effect, which reflects the time effect on economic growth, and ε_{it} represents the disturbance term.

(2) Temporal accumulation effect of HSR construction

There is often a time lag when the economic effect of HSR appears, since such impacts as improvement of the overall transportation system, acceleration of production factors' flow and the perfection of the industrial structure, all need to take quite a while to be reflected. Accordingly, to test the temporal accumulation effect of HSR operation, we propose the following model:

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 dur_{it} + \beta_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

where dur_{it} denotes the cumulative operation period of HSR in city i. Based on the sample observation period (2009–2019) in this paper, dur_{it} can be calculated as follows:

$$dur_{it} = \begin{cases} t^{year} - \left[t_0^{year} + \left(t_0^{month}/12\right)\right], & t^{year} > t_0^{year} \\ 0 & , t^{year} \le t_0^{year} \end{cases} \quad (3)$$

where t^{year} is the year of observation time, and t_0^{year} and t_0^{month} represent the year and month of HSR opening respectively.

(3) The impact of HSR construction on regional economic development gap

In order to test whether HSR opening will narrow the gap among cities or widen the gap, we propose a multi-temporal DID model. In the model, we define gap_{it} as the regional economic development gap, which is expressed by the deviation of economic growth rate and can be calculated by the difference between the economic growth rate of city i in year t and the average economic growth rate of all cities in the same year. Economic growth rate refers to the year-on-year growth rate of GDP per capita of a city over the previous year. Accordingly, the model is constructed as follows:

$$gap_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (4)$$

4.2 Mediation effect analysis of HSR construction

To further investigate the influence path of HSR construction on regional economic development, we carry out mediation effect analyses regarding such mediating factors as industrial structure and urbanization level.

1) Mediation effect analysis regarding industrial structure upgrading

The construction of HSR has a profound influence on the industrial structure of cities along the line. The HSR service can improve the transportation accessibility among regions, promote the connection among cities, and further increase the tourism, real estate and retail industries of cities along the line, which may thus promote the transfer of the secondary industry to the tertiary industry. Also, the construction of HSR can accelerate the flow rate of people, capital and information, and further upgrade the industrial structure. Accordingly, we use the industrial structure upgrading index to evaluate the industrial structure level (denoted by TS_{it}), which can be calculated by multiplying the proportion of the added value of the three industries in GDP by the corresponding weights.

In order to explore whether the opening of HSR can promote the upgrading of industrial structure of regional cities, and then improve the level of economic development of regional cities, we establish a mediating effect model as follows:

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (5)$$

$$TS_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (6)$$

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 TS_{it} + \beta_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (7)$$

where Eq. (5) aims to test whether the HSR opening has an impact on the regional economic development level, Eq. (6) aims to test whether the HSR opening has an impact on the industrial structure upgrading index, and Eq. (7) further aims to test whether the HSR opening has an impact on the regional economic development level through promoting the industrial structure upgrading index.

2) Mediation effect analysis regarding urbanization level promotion

HSR has played a fundamental role in improving the urbanization level. The construction and operation of HSR can work to improve transport accessibility among cities and accelerate the flow of production factors, and thus enhance the attractiveness of urban cities, which further promote more migration to urban cities and improve the urbanization level. At the same time, the improvement of urbanization level brings about the increase of labor force and the expansion of domestic demand, which further promoted the development of regional economy. Accordingly, we use the urbanization rate (denoted by CZ_{it}) to represent the level of urbanization, which can be calculated according to the proportion of urban population to the total population.

In order to verify whether HSR construction has an impact on the level of urbanization, and then improve the level of regional economic development, we establish a mediating effect model as follows

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (8)$$

$$CZ_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (9)$$

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 CZ_{it} + \beta_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (10)$$

where Eq. (8) aims to test whether the HSR opening has an impact on the regional economic development level, Eq. (9) aims to test whether the HSR opening has an impact on the urbanization level, and Eq. (10) further aims to test whether the HSR opening has an impact on the regional economic development level through promoting the urbanization level.

4.3 Spatial spillover effect analysis of HSR construction

If we only consider the economic development of HSR along the line, we ignore the spatial effect of HSR. HSR construction not only plays an important role in the development of the city itself, but also has a certain spatial spillover effect on the surrounding areas. Therefore, this paper introduces the spatial dimension into the empirical study to investigate the spatial spillover effect of HSR construction in Hubei Province. In order to discuss whether HSR construction has a spatial spillover effect on the level of regional economic development, we have constructed the following Spatial Durbin model:

$$Y_{it} = \beta_0 + \beta_1 HSR_{it} + \beta_2 X_{it} + \rho_0 W_{ij} Y_{jt} + \rho_1 W_{ij} HSR_{jt} + \rho_2 W_{ij} X_{jt} + \mu_i + \gamma_t + \varepsilon_{it} \quad (11)$$

where W_{ij} is the standardized spatial weight matrix, and ρ_0 is the estimation coefficient corresponding to $W_{ij} Y_{jt}$, which indicates the effect of the economic development of neighboring areas on the local area and is used to measure the spatial spillover effect of the economic development level. In Eq. (11), ρ_1 is the estimation coefficient corresponding to $W_{ij}HSR_{jt}$, which indicates the effect of the HSR opening variables in the neighboring areas on the local area, and is used to measure the spatial spillover effect of the HSR opening policy on the neighboring economic development level. Besides, ρ_2 is the estimation coefficient corresponding to $W_{ij}X_{jt}$, which indicates the effect of the control variables in the neighboring areas on the local area and is used to measure the spatial spillover effect of the control variables on the economic development level of the neighboring areas.

Different weight matrices will lead to different results. In the model, we apply the inverse distance spatial weight matrix. The weight can be calculated according to the reciprocal value of the distance as follows:

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}}, i \neq j \\ 0, i = j \end{cases} \quad (12)$$

where d_{ij} is the distance between city i and city j. In order to further investigate the influence of distance on the spatial spillover effect, we define the spatial weigh matrix with spatial distance threshold as follows:

$$W'_{ij} = \begin{cases} \frac{1}{d_{ij}}, i \neq j \text{ and } d_{ij} \leq d \\ 0, i = j \text{ or } d_{ij} > d \end{cases} \quad (13)$$

where d denotes the spatial distance threshold, which takes the interval of 50 km from 150 to 450 km.

4.4 Description of main variables

(1) Dependent variables

Level of economic development (Y_{it}) is expressed by nighttime lighting data. Nighttime lighting data can objectively reflect industrial production, commercial activities, energy consumption and other aspects, and can be used to measure the economic development level of a region. At the same time, in order to verify the stability of the data, Gross domestic product (GDP) per capita is also used to represent the level of regional economic development in the process of data analysis.

The gap of regional economic development level (gap_{it}) is expressed by the deviation of economic growth rate. The deviation of economic growth rate is the difference between the economic growth rate of a city in that year and the average of all cities in that year.

(2) Explanatory variables

HSR opening policy (HSR_{it}): As a powerful means to shorten the travel time between cities and improve urban accessibility, the opening of HSR plays a key role in urban economic growth. The opening of HSR has profoundly affected the economic activities of the region and the city. Promote industrial agglomeration (Li et al. 2017), accelerate the flow of capital factors (Bian et al. 2018), and produce growth effects and structural effects on regional economic spillover and economic spatial structure (Wang et al. 2016). It has improved the efficiency of human resource allocation and effectively promoted the economic growth of the city.

HSR cumulative running time (dur_{it}): The effect of large transport infrastructure such as HSR on regional economic growth tends to be gradual over time. Therefore, based on the sample observation period (2009-2019), this paper calculates the time from the start of operation to the observation period of each city and state HSR in Hubei Province and incorporates this variable into the measurement equation.

Industrial structure (TS): Industrial structure upgrading is the main driving force for regional economic growth

(Yu 2015). Some scholars also pay attention to the role of transportation infrastructure, especially HSR, in the process of industrial structure upgrading (Sun et al. 2022). The opening of HSR can aggravate the level of urban sprawl. High land rent, high wages and low industrial agglomeration benefit lead to the location transfer of manufacturing industry to small and medium-sized cities with lower cost, causing the proportion of service industry to rise while the proportion of manufacturing industry to decline, thus changing the proportion of secondary and tertiary industries and affecting the industrial structure (Jiang et al. 2017). On the other hand, the optimization and upgrading of industrial structure also have an important impact on the economic development of regional cities.

Urbanization level (CZ): The doubling of the speed of HSR makes the station city effectively get rid of the constraint of geographical location, the urban accessibility and radiation effect are greatly improved, and the interregional flow of population and other factors is effectively promoted, which can effectively expand the urban development space, reduce the commuting cost of residents, improve the urban carrying capacity and attraction, and promote the migration of population to the city. The construction and development of HSR plays a basic role in promoting the level of urbanization. At the same time, the improvement of the level of urbanization has brought about the increase of labor force, the expansion of domestic demand, and further promoted the development of regional economy.

(3) Control variables

Following the research of Bian et al. (2018), Wang et al. (2016), and Bian et al. (2019), such indicators as labor force, consumer market scale and so on are selected as control variables. Among these indicators, the concentration of labor force can improve productivity and promote economic development. The scale of consumption market is an important index to evaluate the domestic consumption market. Capital investment is an important factor to be considered in economic growth. Capital investment can affect the economic output of a city through industrial correlation and technology spillover effect. Investment in technology is also an important factor for high-quality economic development; Infrastructure construction level play an important role in regional economic growth. The construction and transformation of public infrastructure promote urban economic growth. The level of education reflects the development of society and the improvement of quality. The selected control variables are defined as follows:

Labor force (L): Labor force agglomeration can promote the aggregation of economic factors, better optimize the allocation of urban human resources, thereby improving productivity and promoting regional economic development. It is expressed by the population density of each city and processed by logarithm.

Consumer market scale (M): The total retail sales of consumer goods is one of the most important indicators to observe the level of domestic consumption, and consumption plays a basic role in economic growth. It is expressed by the proportion of total retail sales of social consumer goods to GDP in each city.

Capital investment (F): In this paper (Bian et al. 2018), considering the main sources of capital formation in a region. It is expressed by the investment in fixed assets of each city, and is processed by logarithm.

Infrastructure construction level (R): In consideration of the availability of data, this paper refers to (Bian et al. 2019), which is expressed by the expressway mileage of prefecture-level cities owned by the city per person.

Education quality (E): Economic growth comes not only from an increase in the quantity of factors such as capital and labor, but also from an improvement in the quality of education. Education, especially higher education, contributes to productivity by producing a highly qualified workforce. It is expressed by the number of students in ordinary colleges and universities in each city (the unit is ten thousand), and it is processed by logarithm.

Investment in technology (T): The existing literature used to directly measure the number of patent grants and applications published by the National Patent Office. It is expressed by the proportion of fiscal expenditure on science and technology, research and development in each city to GDP.

Enterprise competitiveness (C): The increase of enterprise scale and strength is conducive to the improvement of competitiveness and the long-term development of enterprises. It is expressed by the number of industrial enterprises above designated size in each city, and processed by logarithm.

(4) Sample selection and variable descriptive analysis

In this paper, we choose Hubei Province as the research case area, and select data from 16 cities in Hubei Province, mainly including Wuhan, Xiaogan, Ezhou, Jingzhou, Huangshi, Huanggang, Xianning, Tianmen, Qianjiang, Xiantao, Yichang, Xiangyang, Suizhou, Shiyan and Enshi. Because some data in Shennongjia forest area are seriously missing, it is excluded. The research time period is chosen from 2009 to 2019, using the official opening time of Wuhan-Guangzhou section of Beijing-Guangzhou HSR line in 2009 as the research start point. Due to the force majeure caused by the COVID-19 epidemic in Hubei Province from 2020 to 2022, there was a long-term suspension of HSR, which affected economic development (see Shi 2023). In order to ensure the accuracy of the HSR data, we chose 2019 as the research deadline.

GDP is one of the core analysis variables in macroeconomics, but in practice, there are some inevitably measurement deviations due to the defects of statistical data reporting mechanism. In recent years, nighttime light data has been widely used in the measurement of total economic activities in the field of social science, which has greatly improved the accuracy of statistical indicators such as economic growth and produced a large number of research results (see Henderson et al. 2012, Xu et al. 2015). The applicability of satellite light data is discussed by using cross-border panel data of the past two decades. To compare the difference between satellite light data and official statistics in calculating national income growth. They found a significant positive correlation between the brightness of a country's satellite lights and its GDP. Donaldson et al. (2016) also pointed out that nighttime light data, as a kind of geospatial raster data, breaks through the restrictions of administrative boundaries compared with traditional data such as GDP and can reflect the dynamic changes of economic activities in geospatial dimensions. It has been widely used in the fields of development economics, economic history, spatial and urban economics, and has vigorously promoted the theoretical and empirical research work in related fields. Accordingly, we use nighttime light data instead of traditional GDP indicators to measure economic growth in this research.

The most widely used and recognized source of nighttime light data are from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) sensor and the Visible Infrared Imaging Radiometer Suite sensor on board the National Polar-Orbiting Partnership (NPP/VIIRS) satellite. Compared to the DMSP/OLS data, NPP/VIIRS data exhibit higher spatial resolution and more accurate radiometric measurements, with reduced saturation issues in urban centers. Besides, the nighttime light data from DMSP/OLS and NPP/VIIRS covers different time spans. Specifically, the DMSP/OLS data covers the time period from 1992 to 2013, and NPP/VIIRS starts to provide data since 2012. For the needs of this study, we select the nighttime lighting data of DMSP/OLS between 2009 and 2012, and that of NPP/VIIRS between 2012 and 2019 as proxy variables of economic development level. The main variables in the model are listed above, and the descriptive statistics on the sample variables are shown in Table 1.

In order to avoid the multicollinearity problem, stepwise regression method is used in this paper. Stepwise regression is widely used in economic models. The stepwise regression method is to test the significance of variables through partial regression sum of squares to consider whether to introduce or remove variables, and the test of partial regression sum of squares can be generally unified with the multicollinearity test between variables.

Table 1 Descriptive statistics and analysis of model variable

Variable	Minimum	Maximum	Mean	Standard deviation
Level of economic development	0.530	3.370	1.820	0.631
HSR opening policy	0.000	1.000	0.790	0.409
HSR cumulative running time	0.000	10.75	3.637	3.167
Labor force	4.920	7.177	5.975	0.552
Consumer market scale	0.261	0.708	0.446	0.094
Capital investment	0.021	5.701	1.233	1.182
Infrastructure construction	0.001	0.009	0.004	0.002
Education quality	0.002	0.095	0.015	0.020
Investment in technology	0.014	0.087	0.029	0.013
Enterprise competitiveness	5.187	7.996	6.630	0.641
Industrial structure	1.199	3.012	2.235	0.170
Urbanization level	0.308	0.805	0.528	0.103

4.5 Model robustness tests

4.5.1 Parallel trend test

Before the baseline regression analysis, we first test the parallel trend hypothesis. We add the policy dummy variables at each time point into the regression. If the coefficient of the variable before the policy is not significant, it indicates the existence of parallel trends. From Fig. 1, it can be seen that the changes of the curve are relatively stable with little change before the base period of the HSR opening policy implementation. But after the implementation of the HSR open policy, the curve gradually moves up, indicating that the parallel trend hypothesis is satisfied.

4.5.2 Replacement of the dependent variable

In order to prove the reliability of nighttime lighting data, we substitute the dependent variable with the real GDP per capita of each city. According to Table 2, When we add control variables in turn, the regression results still have strong stability. The results show that the development of HSR in Hubei Province has a positive effect on the real GDP per capita of each city, and its effect still exists at the significance level of 1%. According to the regression analysis, compared with the cities without HSR, the real GDP per capita of the cities with HSR increase significantly. The real GDP per capita of all cities

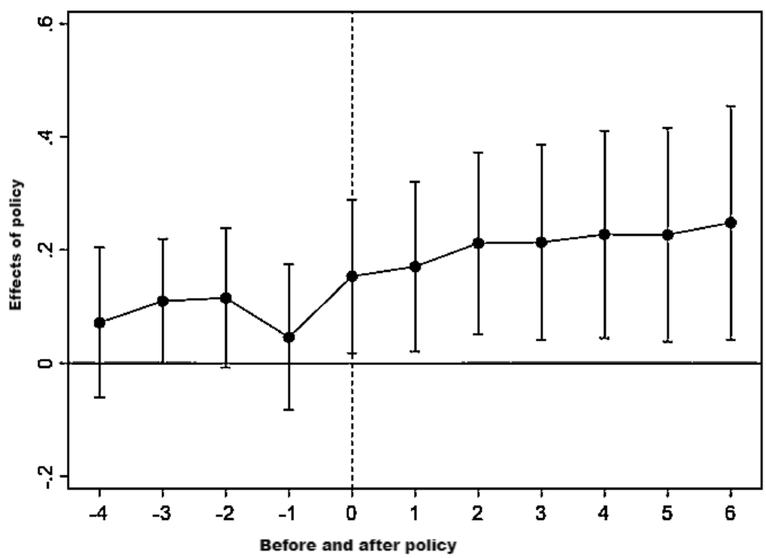

Fig. 1 Parallel trend hypothesis testing

Table 2 The regression results of replace the dependent variable

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
HSR	0.073***	0.053***	0.054***	0.056***	0.056***	0.057***	0.056***	0.056***
	(5.00)	(3.85)	(3.88)	(3.94)	(3.91)	(3.92)	(3.90)	(3.88)
Labor force		-0.904**	-0.906***	-0.897***	-0.892***	-0.903***	-0.935***	-0.940***
		(-5.76)	(-5.75)	(-5.67)	(-5.52)	(-5.52)	(-5.69)	(-5.73)
Consumer market scale			-0.047	-0.044	-0.047	-0.042	-0.136	-0.130
			(-0.54)	(-0.51)	(0.53)	(-0.47)	(-1.24)	(-1.19)
Capital investment				0.003	0.003	0.003	0.004	0.003
				(0.75)	(0.74)	(0.69)	(0.88)	(0.74)
Infrastructure construction					1.772	2.555	3.935	6.567
					(0.14)	(0.21)	(0.32)	(0.52)
Education quality						-1.031	-0.479	-0.614
						(-0.50)	(-0.23)	(-0.29)
Investment in technology							1.785	2.052*
							(1.51)	(1.71)
Enterprise competitiveness								0.054
								(1.23)
_cons	9.824***	15.23***	15.26***	15.20***	15.17***	15.24***	15.41***	15.07***
	(817)	(16.2)	(16.2)	(16.1)	(15.6)	(15.4)	(15.6)	(14.7)
Year fixed effect	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
City fixed effect	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
N	176	176	176	176	176	176	176	176
R^2	0.988	0.990	0.990	0.990	0.990	0.990	0.990	0.990

Remarks: ***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

in Hubei Province is consistent with the baseline regression estimation results of nighttime light data, which indicates that the model estimation results using nighttime light data are robust.

4.5.3 Placebo test

When the policy timing is advanced, the regression coefficient is not significant, which shows that the policy is effective and in turn verifies the robustness of the conclusion. The results in Table 3 show that the opening of HSR has no significant promoting effect on the level of economic development after the assumed policy time point is advanced 4 and 5 periods, which confirms the policy effect brought by the opening of HSR from the side.

5 Empirical results analysis

5.1 Preliminary test of the direct economic impact of HSR construction

5.1.1 Direct effect analysis of HSR opening on economic development level

Table 4 shows the regression results of the opening of HSR on the economic development level of Hubei Province. Without adding control variables, Column (1) shows that the coefficient of HSR opening variable is significant. Columns (2)-(8) show the results when adding the related control variables successively. The results indicate that the impact of HSR opening variable on the nighttime light data is positively promoted, and is significant at the 1% level. It shows that the opening of HSR has a significant role in promoting the economic development level of cities in Hubei province.

From the perspective of control variables, the influence coefficient of population density, total retail sales of consumer goods and fixed asset investment on the economic development level is positive and significant. The concentration level of labor force and capital input have significant impact on regional economic development. This is in line with the neoclassical economic growth theory that the urban economic growth level increases with the input of labor and investment factors. The scale of consumption market has a significant impact on regional economic development. Consumption plays a fundamental role in economic development. The further expansion of domestic demand promotes the accelerated flow of resources and the upgrading of production. The level of infrastructure construction has a significant impact on regional economic development. The construction of expressways has promoted close exchanges among cities, supplemented the shortcomings of "door-to-door transportation" of HSR, and promoted investment and economic growth. After columns (2)-(8) are successively added with control variables, compared with column (1), the influence coefficient of HSR construction on the level

Table 3 The regression results of four and five policy points in advance

Explanatory variables	(1) No control variables	(2) No control variables	(3) With control variables	(4) With control variables
HSR-4	-0.031 (-0.76)		-0.018 (-0.43)	
HSR-5		-0.028 (-0.52)		0.002 (0.04)
Labor force			0.191** (1.08)	0.200 (1.12)
Consumer market scale			0.246* (1.96)	0.232* (1.88)
Capital investment			0.013*** (2.61)	0.013*** (2.64)
Infrastructure construction			-58.80*** (-4.22)	-58.40*** (-4.19)
Education quality			1.257 (0.53)	1.179 (0.50)
Investment in technology			-3.492*** (-2.60)	-3.515*** (-2.62)
Enterprise competitiveness			-0.035 (-0.70)	-0.031 (-0.63)
_cons	1.611*** (42.67)	1.609*** (32.54)	0.855 (0.76)	0.765 (0.67)
Year fixed effect	*YES*	*YES*	*YES*	*YES*
City fixed effect	*YES*	*YES*	*YES*	*YES*
N	176	176	176	176
R^2	0.939	0.939	0.950	0.950

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 4 The direct effect of HSR construction on the level of economic development

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
HSR	0.041***	0.049***	0.051***	0.062***	0.055***	0.054***	0.055***	0.056***
	(2.59)	(3.03)	(3.10)	(3.84)	(3.50)	(3.46)	(3.61)	(3.62)
Labor force		0.364*	0.361*	0.408**	0.289*	0.309*	0.370**	0.373**
		(1.97)	(1.95)	(2.28)	(1.64)	(1.73)	(2.11)	(2.12)
Consumer market scale			-0.084	-0.071	0.023**	0.014	0.196*	0.193*
			(-0.83)	(-0.72)	(0.24)	(0.14)	(1.68)	(1.64)
Capital investment				0.017***	0.018***	0.018***	0.016***	0.017***
				(3.37)	(3.60)	(3.65)	(3.34)	(3.40)
Infrastructure construction					-46.65***	-48.02***	-50.70***	-52.41***
					(-3.50)	(-3.57)	(-3.84)	(2.25)
Education quality						1.812	0.739	0.827
						(0.80)	(0.33)	(0.37)
Investment in technology							-3.469***	-3.645***
							(-2.75)	(-2.83)
Enterprise competitiveness								-0.035
								(-0.75)
_cons	1.574	-0.599	-0.549	-0.844	-0.011	-0.142	-0.472	-0.248*
	(121.4)	(-0.54)	(-1.70)	(-0.79)	(-0.01)	(-0.13)	(-0.45)	(-0.23)
Year fixed effect	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
City fixed effect	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
N	176	176	176	176	176	176	176	176
R^2	0.941	0.943	0.943	0.947	0.951	0.952	0.954	0.954

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

of regional economic development shows an increasing trend. And the effect of HSR is more obvious under the superposition of various factors.

5.1.2 Temporal accumulation effect of HSR construction

There is often a time lag when the HSR investment play an impact on regional economic development. Therefore, we analyze the temporal accumulation effect of HSR during the observation period and conducted regression analysis. From Table 5, we can see that the influence coefficient of cumulative running time of HSR rail transit is positive, and it is significant at the level of 1%, whether the dependent variable is nighttime lighting data or real GDP per capita. The results show that HSR has an obvious positive effect on regional economic growth. And with the extension of cumulative running time, its effect on regional economic growth is gradually enhanced, showing an obviously temporal accumulation effect.

Table 5 The regression results of temporal accumulation effect of HSR construction

	(1) Nighttime lighting data	(2) Real GDP per capita
HSR	0.047*** (3.00)	0.060*** (4.09)
HSR cumulative running time	0.035** (2.21)	0.019* (1.30)
_cons	-2.279 (-0.26)	15.09*** (14.72)
Control variables	*YES*	*YES*
Year fixed effect	*YES*	*YES*
City fixed effect	*YES*	*YES*
N	176	176
R^2	0.956	0.990

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

We find that in column (1) of Table 6, the opening of HSR in 2010 and 2011 had an insignificant influence coefficient on the nighttime light data. It indicates that the impact of HSR on regional economic development is lagging, and the environmental impact of HSR construction in a short period of time might not be obvious and be ignored. However, with the development of HSR in the later period, the development of HSR after 2012 has a significant impact on the nighttime light data at the level of 1%. It indicates that with the opening of HSR, the impact on regional economic development level in a long time span is significant.

Table 6 The regression results of annual cross-sectional data of HSR construction

	(1) Nighttime lighting data	(2) Real GDP per capita
HSR	0.047*** (3.00)	0.060*** (4.09)
HSR × 2010	-0.027 (-1.55)	0.184*** (11.02)
HSR × 2011	-0.010 (-0.44)	0.440*** (20.12)
HSR × 2012	0.096*** (3.73)	0.565*** (23.37)
HSR × 2013	0.184*** (6.86)	0.658*** (26.03)
HSR × 2014	0.214*** (6.66)	0.757*** (25.77)
HSR × 2015	0.226*** (6.43)	0.831*** (25.15)
HSR × 2016	0.230*** (6.09)	0.915*** (25.68)
HSR × 2017	0.377*** (9.44)	1.031*** (27.45)
HSR × 2018	0.413*** (9.99)	1.154*** (29.62)
HSR × 2019	0.485*** (10.99)	1.245*** (29.97)

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 7 The Regression results of the impact of HSR construction on economic development gap

	(1)	(2)
HSR	0.016* (1.87)	0.017** (2.21)
Labor force		0.129 (1.44)
Consumer market scale		0.138** (2.31)
Capital investment		7.289 (1.07)
Infrastructure construction		1.426 (1.24)
Education quality		0.004* (1.62)
Investment in technology		0.102 (0.16)
Enterprise competitiveness		-0.136*** (-5.65)
_cons	0.031*** (4.41)	0.048 (0.08)
Year fixed effect	*YES*	*YES*
City fixed effect	*YES*	*YES*
N	176	176
R^2	0.229	0.464

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

5.1.3 The impact of HSR construction on regional economic development gap

In order to further explore the impact of HSR opening on the regional economic development gap in Hubei Province, columns (1)-(2) in Table 7 show the relationship between HSR opening and regional economic development gap without and with the addition of control variables. The regression coefficients of HSR opening variables are significantly positive. It indicates that HSR construction has widened the gap of regional economic development among cities to some extent.

5.2 Heterogeneity analysis results of direct economic effect of HSR construction

Based on the empirical study on the impact of HSR construction on the economic growth of Hubei Province, the heterogeneity of the impact of HSR opening on the economic development of different levels of cities, metropolitan areas and development zones in Hubei Province is further verified by grouping the research objects and adjusting the model.

5.2.1 Heterogeneity analysis regarding core-periphery cities

The opening of HSR may have different impacts on the economic development of different levels of cities. Hubei Province is pushing forward the regional development layout of "one main leading, two wings driving, and all-region coordination". This will further enhance the comprehensive carrying capacity of central cities and urban agglomerations, improve the level of regional central cities, and build a new urbanization pattern of coordinated development of large, medium and small cities.

The New Urbanization Plan of Hubei Province (2021–2035) divides cities into different levels according to their geographical location, economic strength, city size and radiation range. Wuhan is the national central city, and Xiangyang and Yichang are provincial sub-central cities. Six comprehensive regional central cities (Huangshi, Shiyan, Jingzhou, Xiaogan, Jingmen and Huanggang) and seven characteristic regional central cities (Ezhou, Xianning, Suizhou, Enshi, Xiantao, Qianjiang and Tianmen) have been initially identified. Different levels of cities have different influences on the region, and the six comprehensive regional central cities assume the corresponding radiation leading range in different regions. Huangshi is the central city in the middle reaches of the Yangtze River. Shiyan is the central city in the area adjacent to Hubei, Henan, Shaanxi and Chongqing. Jingzhou is the central city in the Lianghu Plain. Xiaogan is the sub-center of Wuhan City Circle. Jingmen is the central city in central Hubei, and

Huanggang is the core city in the Dabieshan old revolutionary base area. Compared with seven characteristic regional central cities, their city scales, transportation advantages and economic foundation are relatively good. Based on the above analysis, we select Wuhan, Xiangyang, Yichang, Huangshi, Xiaogan, Shiyan, Jingzhou, Jingmen, Huanggang as the central cities, and divide Ezhou, Xianning, Suizhou, Enshi, Xiantao, Qianjiang and Tianmen into peripheral cities.

From columns (1)-(2) in Table 8, we can see that the opening of HSR has heterogeneous effects on the economic development level of different scale cities. The coefficient of the opening of HSR on the economic development level of the central city is 0.090, and is significant at 1% level. The absolute value of variable coefficient of HSR opening in central cities is greater than that of peripheral cities. Compared with peripheral cities, HSR opening plays a greater role in promoting economic development of central cities. The resource gathering capacity of central cities is greater than that of peripheral cities. The development of HSR promotes the transfer of many high-quality resource elements to central cities, strengthens the siphon effect, and widens the development gap among cities.

Table 8 Heterogeneity analysis based on core-periphery cities

	Core cities	**Periphery cities**
HSR	0.090*** (4.02)	0.048* (1.97)
_cons	1.869 (1.10)	-5.213*** (-2.79)
Control variables	*YES*	*YES*
Year fixed effect	*YES*	*YES*
City fixed effect	*YES*	*YES*
N	99	77
R^2	0.996	0.997

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

5.2.2 Heterogeneity analysis based on different metropolitan areas

Metropolitan area is not only an important spatial form of urbanization development, but also the core component of urban agglomeration. Metropolitan area is an important carrier of urban population in China, which is conducive to promoting the spatial distribution of urban population and economy and forming a coordinated urbanization spatial development pattern. The 12th Hubei Provincial Congress proposed to speed up the construction of three metropolitan areas with Wuhan, Xiangyang and Yichang as the center, and enhance the economic and population carrying capacity of areas with advantages in economic development (central cities, urban agglomeration, etc.). Wuhan metropolitan area is centered in Wuhan and consists of eight cities: Ezhou, Huangshi, Huanggang, Xiaogan, Xianning, Xiantao, Tianmen and Qianjiang. It is the region with the most intensive economic development and the strongest economic strength in Hubei, and it is the core plate of urban agglomeration in the middle reaches of the Yangtze River. Xiangyang metropolitan area, with Xiangyang as the center, is composed of Shiyan, Suizhou and Shennongjia forest areas, which builds an important link between Wuhan metropolitan area and Central Plains urban agglomeration. Yijingjing metropolitan area, with Yichang as the center and Jingzhou, Jingmen and Enshi as the components, will be built into a gateway to the south and west, and become an important link connecting Wuhan metropolitan area and Chengdu-Chongqing dual economic circle.

In order to further explore the impact of HSR on the economic development level of Hubei metropolitan areas, the cities in Hubei Province are grouped according to the three metropolitan areas. Columns (1)-(3) in Table 9 show the impact of HSR opening on regional economy in Wuhan, Xiangyang and Yijingjing Metropolitan areas. The coefficient of the opening of HSR on

Table 9 Heterogeneity analysis results based on different metropolitan areas

	Wuhan metropolitan area	**Xiangyang metropolitan area**	**Yijingjing metropolitan area**
HSR	0.075*** (3.00)	0.006 (0.18)	0.0181 (0.44)
_cons	-2.607 (-1.47)	11.66* (2.02)	6.416 (1.37)
Control variables	*YES*	*YES*	*YES*
Year fixed effect	*YES*	*YES*	*YES*
City fixed effect	*YES*	*YES*	*YES*
N	99	33	44
R^2	0.995	0.994	0.993

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

the economic development level of Wuhan metropolitan area is statistically significantly positive, which indicates that the opening and construction of HSR promote the economic development of Wuhan metropolitan area. The infrastructure of various cities in Wuhan metropolitan area has been interconnected. Wuhan has established highway network, HSR construction or urban rail network with eight surrounding cities, giving full play to the radiating and driving role of core cities, deepening innovation collaboration, industrial cooperation and market linkage, and further improving the level of economic development. The coefficient of the opening of HSR on the economic development level of the other two metropolitan areas is not statistically significant. Compared with Wuhan metropolitan area, the level of infrastructure connectivity within Xiangyang and Yijingjing metropolitan area is lower. However, the connectivity between the two metropolitan areas is being accelerated. With the opening of the Zhengwan HSR, the Xiangyang metropolitan area has realized HSR connectivity among four areas. The Wuyi section of the HSR along the Yangtze River, the Jingjing HSR and the link line between Yichang and Zhengwan HSR in the Yijingjing metropolitan areas are also under orderly construction.

5.3 Further test of mediation effect analysis of HSR construction

To further investigate the influence path of HSR construction on regional economic development and illustrate the mediation effects of industrial structure and urbanization level, we conduct empirical studies by applying the mediating effect model (5)-(10).

5.3.1 *Mediation effect analysis results of industrial structure upgrading*

Table 10 shows the regression results based on the mediation effect model (5)-(7). It can be seen from column (1) and column (2) of Table 10, the opening of HSR has a significant positive effect on urban economic development level and the upgrading of industrial structure. Thus, we suppose that HSR construction promotes the upgrading of urban industrial structure, which further promotes the urban economic development. But the result in column (3) shows that the effect of industrial structure on regional economic development level is not significant, which implies the mediation effect of industrial structure is not significant. However, the above stepwise regression method is often argued by scholars that sometimes the test efficiency is not enough. Since there exists the case that the stepwise regression result shows the mediating effect is not significant, but the mediating effect actually works. Accordingly, we further apply the bootstrap test

Table 10 The result of the mediating effect of industrial structure

Dependent variable	(1) Economic development level	(2) Industrial structure	(3) Economic development level
HSR	0.056*** (3.62)	0.093*** (2.53)	0.049*** (4.44)
Industrial structure			-0.033 (-1.33)
_cons	-0.248* (-0.23)	1.931 (0.73)	5.348*** (6.84)
Control variables	*YES*	*YES*	*YES*
Year fixed effect	*YES*	*YES*	*YES*
City fixed effect	*YES*	*YES*	*YES*
N	176	176	176
R^2	0.954	0.763	0.994

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

to further analyze whether industrial structure plays a mediating role in the impacts of HSR construction.

Table 11 shows the results of the further bootstrap test. In the test, 95% confidence interval of mediating effect is obtained through 1000 repeated random sampling. The results show that the coefficient of mediating effect is significantly positive, and does not include 0 between the upper and lower limits of 95% confidence level, which indicates that there exists a mediating effect, and the mediating effect and direct effect are both significant at 1% level. And HSR construction affects the economic development level of cities in Hubei province with 7.986% industrial structure upgrading level.

5.3.2 *Mediation effect analysis results of urbanization level*

Table 12 shows the regression results based on model (8)-(10). The result in column (1) shows that the HSR construction has a significant impact on regional economic development level. And in column (2), it can be observed that the impact of HSR construction on urbanization can be observed. The regression coefficient of the HSR opening variable is significantly positive, indicating that the construction of HSR improves urban accessibility and accelerates urban population agglomeration. Compared with cities without HSR, the HSR construction promoted the urbanization level of cities in Hubei Province to increase by 0.022.

And it can be seen from column (3) that the coefficient of HSR opening variable and the urbanization level variable are 0.046 and 0.451. The former is significant at the significance level of 1% and the latter is significant at the significance level of 5%. Consequently, the above analysis indicates that HSR construction can effectively promote economic development through improving the level

Table 11 The mediating effect test of industrial structure level

	*a*b* (95%Boot CI)*	Conclusion	*c* Total effect	*a*b* mediating effect	*C′* Direct effect	Formula of effect proportion	Effect proportion
Industrial structure	0.005 ~ 0.030	Partial mediation	0.379**	0.030***	0.349**	*a*b/c*	7.986%

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 12 The regression results of the effect of HSR construction on urbanization level

Dependent variable	(1) Economic development level	(2) Urbanization level	(3) Economic development level
HSR	0.056*** (3.62)	0.022*** (3.34)	0.046*** (2.90)
Urbanization level			0.451** (2.36)
_cons	-0.248* (-0.23)	-0.898* (-1.88)	0.156 (0.14)
Control variables	YES	YES	YES
Year fixed effect	YES	YES	YES
City fixed effect	YES	YES	YES
N	176	176	176
R^2	0.954	0.854	0.956

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

of urbanization, which implies urbanization level plays a mediating role. Moreover, in order to further explore the mediating effect, we use bootstrap sampling to test the mediating effect. According to the results in Table 13, HSR construction affects the economic development level of cities in Hubei Province with the urbanization level of 44.38%.

5.4 Further test of spatial spillover effect of HSR construction

5.4.1 Spatial correlation test of economic development level

We use Moran's I index to test the spatial correlation of the economic development level of cities in Hubei Province. The specific calculation formula is as follows:

$$Moran's\, I_{it} = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_{it}-\bar{x})(x_{jt}-\bar{x})}{\frac{\sum_{i=1}^{n}(x_{it}-\bar{x})^2}{n}} \tag{14}$$

where x_i and x_j are the economic development levels of city i and city j *respectively*, n is the sample size, and w_{ij} is the spatial weight matrix. The Moran's I value is usually between $[-1, 1]$ to determine whether there is spatial correlation. $I > 0$ indicates a positive spatial correlation, $I < 0$ indicates a negative spatial correlation, and $I = 0$ indicates no spatial correlation. Table 14 shows the results of spatial autocorrelation test of regional economic development level in Hubei Province. It can be seen from Table 14 that all the *P*-values are zero from 2009 to 2019 and all the Z-values are greater than 2.58, which implies the economic development level of cities in Hubei Province has significant positive spatial correlation. From the time trend of Moran's I, it can be seen that the Moran's I of regional economic development in Hubei Province presents a low level fluctuation growth trend.

We plot a scatter chart of the regional Moran's I in 2019 to reflect the correlation of cities in Hubei Province. The result in Fig. 2 is based on the spatial weight matrix (12). The origin of coordinates represents the global Moran's I and distance away from the original point represents the level of significance. The further away from the original point, the higher the significance level. Furthermore, the first and third quadrants respectively represent high-high and low-low agglomeration modes of economic development level, which implies positive spatial correlation. And the second and forth quadrants respectively represent low–high and high-low agglomeration modes of economic development level, which implies spatial anomalies. Accordingly, it can be observed from Fig. 2 that the scatter points of most cities are located in the first and third quadrants, which indicates that the economic development level of cities in Hubei Province has strong spatial autocorrelation, which can be used for subsequent estimation by using spatial econometric model.

5.4.2 Spatial spillover effect analysis based on SDM

As can be seen from the above, the economic development level of cities in Hubei Province has significant spatial correlation. In order to further explore the direction and magnitude of the effect of HSR construction on regional

Table 13 The mediating effect test of urbanization level

	*a*b* (95%Boot CI)*	Conclusion	*c* Total effect	*a*b* mediating effect	*C′* Direct effect	Formula of effect proportion	Effect proportion
Urbanization level	0.151 ~ 0.329	Partial mediation	0.534**	0.237***	0.297***	*a*b/c*	44.382%

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 14 Global Moran's I of economic development level from 2009 to 2019

Year	*Moran's I*	*z*	*p-value**
2009	0.103	3.797	0.000
2010	0.092	3.564	0.000
2011	0.113	4.054	0.000
2012	0.093	3.587	0.000
2013	0.103	3.794	0.000
2014	0.102	3.790	0.000
2015	0.105	3.827	0.000
2016	0.102	3.781	0.000
2017	0.107	3.871	0.000
2018	0.106	3.849	0.000
2019	0.111	3.964	0.000

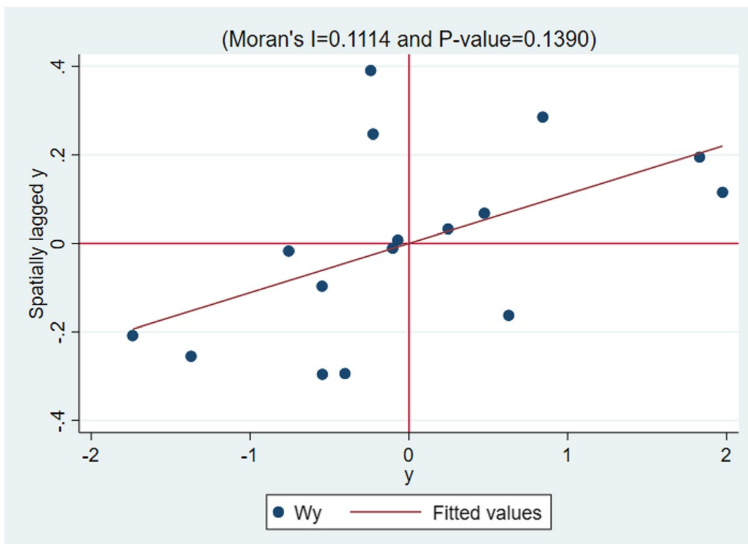

Fig. 2 Moran's I scatter chart of economic development level in Hubei Province in 2019

economic development level, we carry out further empirical analysis through the spatial calculation model.

As shown in Table 15, the results of LM-Lag test, LM-Error test, robust LM-Lag test and robust LM-Error test implies that we can reject the original hypothesis H_0. Based on this result, we can choose the Spatial Durbin model (SDM). Then, the test results are significant in the Hausman test, indicating that the fixed effect model is better. Finally, we use LR test method to test the spatial Durbin fixed effect model. The index values of LR test are 316.09 and 329.03, and H_0 is rejected at the significance level of 1%, indicating that the SDM will not degenerate into a spatial autoregressive (SAR) model and a spatial error model (SEM).

Table 15 Test results of spatial correlation types

	LM-Lag	LM-Error	Robust LM-Lag	Robust LM-Error
LM-test	46.928	34.855	25.436	13.363
P-value	0.000	0.000	0.000	0.000

Based on the above analysis, we apply Spatial Durbin model (SDM) to explore the spillover effect of HSR construction on regional economic development level. Table 16 compares the regression results between DID model without considering the spatial effect and the Spatial Durbin model. It can be seen from Table 16 that the impact of the HSR construction on the economic development level presents a positive effect at the significance level of 1%, but DID model underestimates the promoting effect of the HSR construction since it didn't consider the spatial effect. From the perspective of control variables,

Table 16 Regression results of spatial spillover effect analysis of HSR construction

	(1) Difference-in-differences model	(2) Spatial Durbin model
HSR	0.045*** (0.02)	0.049*** (3.11)
Labor force	0.327*(0.18)	0.498*** (2.66)
Consumer market scale	0.235* (0.13)	0.334*** (2.78)
Capital investment	-0.145 (0.26)	-0.205 (-0.89)
Infrastructure construction	-50.61*** (13.95)	-52.46*** (-3.75)
Education quality	-0 (2.34)	-0.600 (-0.28)
Investment in technology	-3.818*** (1.43)	-4.566*** (-3.65)
Enterprise competitiveness	-0.014 (0.05)	-0.018 (-0.40)
_cons	-0.086 (1.15)	
$W\times y$		0.669*** (9.17)
$W\times$*HSR*		0.148* (0.09)
$W\times$*Labor force*		1.959* (1.78)
$W\times$*Consumer market scale*		0.943* (1.64)
$W\times$*Capital investment*		-1.250* (-1.93)
$W\times$*Infrastructure construction*		43.72 (0.80)
$W\times$*Education quality*		11.49 (1.30)
$W\times$*Investment in technology*		-0.273 (-0.08)
$W\times$*Enterprise competitiveness*		-0.052 (-0.72)

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

the general DID model underestimated the contribution of labor agglomeration level and consumer market size to economic development.

Specially, we will discuss the estimated results of the SDM in detail. The coefficient of $W \times y$ is 0.669, and the autocorrelation coefficient is significant at the level of 1%, indicating that the economic development of cities in Hubei Province has a significant spatial correlation. The coefficient of $W \times HSR$ is 0.148, indicating that the HSR construction has a positive and significant impact on the economic development of cities, and there is a positive spatial spillover effect on economic growth among cities.

The above results can only describe the spatial effects of variables on regional economic development. In order to quantitatively separate direct effect and indirect effect, we further carry out a partial differential decomposition. As shown in Table 17, the direct effect coefficient of the variable of HSR opening is 0.077, and the indirect effect coefficient is 0.564, which are significant at 1% and 5% respectively. This indicates that HSR construction not only promotes the development of HSR cities themselves, but also promotes the development of neighboring cities due to the economic development of HSR cities. The development of HSR has significant spatial spillover effect.

Also, Table 17 shows that the direct and indirect effects of labor agglomeration level and consumer market size are both significantly positive. It indicates that labor agglomeration level and consumer market size have a significant positive spatial spillover effect. Specifically, if the population density and the consumption market scale of the neighboring areas increase by 1% respectively, the economic development level of the region will increase by 0.07033 units or 0.03622 units correspondingly. The increase in labor force and the expansion of the consumer market not only promote the development of the local economy, but also drive the economic development of the neighboring areas. It's because economic agglomeration is beneficial for improving productivity, expanding economic scale, enhancing market scale and potential, and promoting knowledge spillover and technology spillover of cities, which thus promotes the overall improvement of regional economic level. This is consistent with the theoretical viewpoint of new economic geography.

5.4.3 Spatial spillover effect analysis of multi-level traffic circle

In order to explore the boundary of spatial spillover effect of HSR construction on regional economic development level, we set spatial distance thresholds every 50 km within the range of 150 km-450 km, calculate multi-distance spatial weight matrix based on Eq. (13), and use the SDM to carry out continuous regression. Firstly, we calculate the Global Moran's I of economic development level of Hubei Province under different spatial distance thresholds as shown in Table 18 to reveal the spatial correlation characteristics.

It can be seen from Table 18 that the Moran's I of global economic development level under different spatial distance thresholds presents positive significance from 2009 to 2019. And the Z-index test values within the range of 200 km-450 km in 2019 are all greater than 2.58, which indicates that the regional development level of cities in Hubei Province presents significant spatial

Table 17 Decomposition results of direct, indirect effects and total effects

	(1) Direct effect	(2) Indirect effect	(3) Total effects
HSR	0.077***	0.564**	0.641**
	(3.61)	(2.16)	(2.33)
Labor force	0.838***	7.033**	7.872**
	(2.83)	(2.03)	(2.12)
Consumer market scale	0.523***	3.622**	4.146**
	(3.02)	(1.99)	(2.11)
Capital investment	-0.402*	-3.870**	-4.271**
	(-1.73)	(-2.16)	(-2.27)
Infrastructure construction	-53.23***	-4.851	-58.08
	(-3.07)	(-0.03)	(-0.32)
Education quality	1.107	33.73	34.84
	(0.42)	(1.20)	(1.17)
Investment in technology	-5.163***	-11.39	-16.56
	(-3.69)	(-1.02)	(-1.39)
Enterprise competitiveness	-0.029	-0.200	-0.229
	(-0.68)	(-1.04)	(-1.17)

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 18 Moran's I of economic development level under different spatial distance thresholds

Thresholds	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
150 km	0.212 *	0.225 **	0.276 **	0.212 *	0.238 **	0.238 **	2.240 **	0.239 **	0.248 **	0.247 **	0.264 **
	(1.35)	(1.99)	(2.35)	(1.89)	(2.07)	(2.07)	(2.08)	(2.07)	(2.13)	(2.13)	(2.23)
200 km	0.270 ***	0.232 ***	0.279 ***	0.239 ***	0.262 ***	0.253 ***	2.262 ***	0.262 ***	0.277 ***	0.271 ***	0.289 ***
	(2.93)	(2.61)	(3.03)	(2.66)	(2.86)	(2.79)	(2.85)	(2.85)	(2.98)	(2.93)	(3.07)
250 km	0.245 ***	0.205 ***	0.243 ***	0.213 ***	0.233 ***	0.223 ***	0.233 ***	0.233 ***	0.249 ***	0.243 ***	0.258 ***
	(3.07)	(2.69)	(3.08)	(2.76)	(2.95)	(2.86)	(2.95)	(2.95)	(3.10)	(3.04)	(3.18)
300 km	0.277 ***	0.236 ***	0.262 ***	0.240 ***	0.257 ***	0.252 ***	0.261 ***	0.256 ***	0.274 ***	0.269 ***	0.284 ***
	(4.78)	(4.24)	(4.61)	(4.29)	(4.51)	(4.44)	(4.56)	(4.50)	(4.73)	(4.67)	(4.85)
350 km	0.203 ***	0.179 ***	0.209 ***	0.182 ***	0.200 ***	0.196 ***	0.201 ***	0.196 ***	0.207 ***	0.204 ***	0.215 ***
	(4.71)	(4.32)	(4.86)	(4.35)	(4.67)	(4.60)	(4.68)	(4.60)	(4.77)	(4.73)	(4.90)
400 km	0.176 ***	0.159 ***	0.188 ***	0.161 ***	0.175 ***	0.175 ***	0.178 ***	0.175 ***	0.183 ***	0.181 ***	0.188 ***
	(4.60)	(4.29)	(4.86)	(4.32)	(4.58)	(4.59)	(4.63)	(4.57)	(4.72)	(4.68)	(4.79)
450 km	0.156 ***	0.143 ***	0.169 ***	0.145 ***	0.158 ***	0.160 ***	0.161 ***	0.157 ***	0.166 ***	0.164 ***	0.170 ***
	(4.46)	(4.22)	(4.75)	(4.25)	(4.51)	(4.54)	(4.56)	(4.47)	(4.64)	(4.60)	(4.71)

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

agglomeration characteristics. Specifically, the Moran's I shows a decreasing trend with the expansion of spatial distance, indicating that the regional economic development level of Hubei Province presents small-range aggregation characteristics. In addition, from the perspective of time evolution, the Moran's I shows a trend of fluctuation, and the spatial agglomeration degree was enhanced on the whole. During the study period, HSR in some cities of Hubei Province were opened successively, which promoted the closeness of connections among cities and had a certain impact on the correlation of regional economic development level.

Many scholars put forward that the spatial spillover effect of HSR has spatial geographic attenuation characteristics. That is with the increase of distance, the spillover effect of HSR becomes insignificant or even negative. In order to further explore the spatial geographic attenuation boundary of HSR, we decompose the effects of HSR construction under different spatial distance thresholds from 150 to 450 km. As shown in

Table 19 Effect decomposition of HSR construction under different spatial distance thresholds

Thresholds	HSR opening policy variable		
	Direct effect	Indirect effect	Total effect
150 km	0.137*** (7.31)	0.144** (1.70)	0.281*** (2.96)
200 km	0.075*** (3.74)	0.305** (2.34)	0.380*** (2.66)
250 km	0.069*** (3.57)	0.264* (1.89)	0.333** (2.22)
300 km	0.070*** (3.06)	0.283 (1.29)	0.354 (1.50)
350 km	0.077*** (3.41)	0.356 (1.64)	0.432* (1.86)
400 km	0.074*** (3.35)	0.323 (1.46)	0.397* (1.68)
450 km	0.077*** (3.32)	0.418 (1.63)	0.495* (1.81)

***, **, and * are regarded as significance at the level of 1%, 5%, and 10%, respectively

Table 19, the direct effect of HSR construction is significant positive for all the spatial distance thresholds, and the estimation coefficient fluctuates slightly with the increase of the spatial distance threshold. In addition, the indirect effect of HSR is significant at 1% level and 5% level within 200 km and 250 km of geographical distance. However, when the geographical distance exceeds 300 km, the indirect effect is not significant anymore, which implies the spillover effect is not significant. This is because when the distance between cities increases, the marginal cost of the flow of labor, knowledge, information and other factors is increasing, and the spatial spillover effect of HSR construction is gradually reduced.

6 Conclusions and future research

6.1 Conclusions

This paper proposes multi-temporal difference-in-differences model and Spatial Durbin model to analyze the impact of HSR construction on regional economic development in terms of direct effect, indirect effect and spatial spillover effect. The following conclusions are obtained. Firstly, HSR construction has significantly promoted the economic development level of cities in Hubei Province. The impact of HSR construction on regional economic development often lags, which implies the short-term effect is not obvious and easy to be ignored. But when zooming the time span, the impact of HSR construction is significantly positive. Also, HSR construction has widened the gap of regional economic development among cities to some extent. In addition, the impacts of HSR are heterogeneous for different levels of cities and different metropolitan areas. Secondly, HSR construction can effectively improve the level of industrial structure upgrading and urbanization, and further promote regional economic development, which implies industrial structure and urbanization play a mediating role in the impacts of HSR. Thirdly, the economic development level of cities in Hubei Province shows significant positive spatial correlation characteristics. And the spatial spillover effect of HSR promotes the economic development of neighboring cities. But when the geographical distance exceeds 300 km, such spatial spillover effect becomes insignificant.

Based on the above research conclusions, some suggestions are put forward. Firstly, since HSR construction widens the gap between core cities and surrounding small-medium cities as a result of siphon effect, more supporting policies should be tilted to the small-medium cities to enhance their attractiveness when planning HSR lines. Moreover, the core urban agglomeration with Wuhan as the center and Xiaogan as the sub-center should play a radiative role on other cities, and further promote the formation of reasonable industrial division of labor among cities. It implies the non-central cities should pay more attention to the development of secondary industries, and guide the rational flow of labor factors, so as to narrow the gap with the central cities. Finally, on the premise of ensuring smooth communication within subgroups, the interaction of elements among subgroups should be accelerated, the economic relations among subgroups should be strengthened, and the economic complementarity among various regions should be fully brought into play.

6.2 Future research

Although we have explored the impact of Hubei HSR construction on regional economy based on multi-temporal DID model and SDM, the research still has some limitations. First of all, the research area of this paper is Hubei province, and the horizontal comparative study among many regions can be added to future research. Secondly, we use urban attribute data to estimate the interaction among cities, which can not fully reflect the real relationship among cities. Follow-up research can directly carry out quantitative research by using the specific relationship among cities. Thirdly, HSR is more mature in some western developed countries compared with China. In the future research, we can supplement the comparative analysis of domestic and international cases and increase the empirical research of some typical overseas areas. Finally, this paper mainly focuses on the economic impact brought by the opening of HSR in Hubei Province, and lacks research on the evolution characteristics of HSR network and the impact mechanism of HSR network on the economic development level of Hubei Province. Future research could apply the social network analysis methods to further explore the network effect of HSR construction.

Abbreviations

DID Difference-in-differences model
SDM Spatial Durbin model
HSR High-speed Railway

Acknowledgements

This work was supported by the grants from the Ministry of education of Humanities and Social Science Project (No. 21YJC630012). The author is very grateful for the constructive comments of editors and referees.

Authors' contributions

All authors equally contributed to the study conception and design. All authors read and approved the final manuscript.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

All the authors declare that there is no conflict of interest that hinders publication.

Received: 16 October 2023 Revised: 6 March 2024 Accepted: 14 March 2024
Published online: 22 April 2024

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