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Impact of high-speed railway construction on spatial patterns of regional economic development along the route: A case study of the Shanghai–Kunming high-speed railway

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ABSTRACT

The Shanghai–Kunming high-speed railway spans the eastern, central, and western regions of China and is an important "horizontal" in the "eight vertical and eight horizontal" railway network of China. This paper estimates the direct impact of opening a high-speed railway on the spatial patterns of regional economic development along the route by integrating GIS technology, spatial panel data models, and the entropy method. The results show that the high-speed railway can significantly increase the economic aggregate and urbanization rates along the route and promote the upgrading of industrial structures, but it has a limited effect on the economic growth rate, showing a weak trend. In terms of spatial patterns, the high-speed railway significantly improves regional accessibility, the strength of economic ties, and economic potential along the route. The regional economy is characterized by weak spatial agglomeration and presents a trend of balanced development. In general, although the economic effect of HSR for the economically lagged regions is smaller in the short term than that in the economically and less economically developed regions, the high-speed railway has the greatest impact on regional economic development and spatial patterns in economically backward areas, thus the economically backward regions have a greater posterior advantage, which is conducive to balancing regional economies and narrowing regional differences.

1. Introduction

Regional economic development is inseparable from the construction of transportation infrastructure; as a significant fixed assets investment, high-speed railway (HSR) construction can directly drive the development of related regional industries through the investment multiplier effect [1]. On October 1st, 1964, the world's first high-speed railway, Japan's Tokaido Shinkansen, was officially opened for business, and since then, many scholars have conducted various research on the spatial and economic impact of HSR construction, and their results have demonstrated that HSRs can greatly shorten the temporal and spatial distance between the stations, produce a "spatiotemporal compression" effect [2], improve the level of accessibility between regions [3,4], and reduce the costs of enterprise transportation and residents' travel [5].

With increased regional accessibility level along the HSR, the advantages of each part of the region begin to switch, affecting people's residential choices and producers' site selection. The resulting "polarization" and "diffusion" can accelerate the flow of production factors, such as labor, capital, and technology [6]. For example [7], found that as the HSR network reduces commute time, it triggers the relocation of workers' work addresses and an increase in commuters, it indicates that the HSR network has some influence on the flow of labor. Using the Geographic Information System (GIS) and the Difference-In-Differences (DID) model, Hernández and Jiménez [8] found that the agglomeration of capital elements due to HSRs differs depending on the location of the station.

The impact of HSRs on the flow of population and economic elements break the administrative barriers related to population flow and industrial agglomeration, strengthen cooperation, generate exchange and economic links between cities, promote the clustering of urban and

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surrounding industrial zones, and thus change the industrial pattern of the whole region, which is beneficial for the rational allocation of resources and the upgrading and transformation of industrial structures [9–11]. Meanwhile, its resultant "spatiotemporal compression" effect will bring about the "polarization effect" and "diffusion effect" of production factors, which in turn will have an impact on the spatial structure and socioeconomy of the regions along the route. In terms of spatial structure, some scholars have pointed out that the construction of HSRs will accelerate the process of spatial agglomeration and urbanization in nearby cities [12], then the urbanization process will affect regional rainfall, drought and carbon emission [13,14]. It has also been shown that the opening of HSR allows for the transition from mono-functional to multi-functional centers along the line [15]. Regarding the impact of HSRs on regional economies, it is mainly divided into two aspects: regional economic growth and balanced regional economic development. Regarding economic growth, most scholars believe that the construction of HSRs has a positive effect on the growth of regional economies [16–18]. [19] used the structural equation modeling method to measure the impact of HSRs in Spain and proved that HSR investment could stimulate GDP growth and increase employment levels. Chen [20] applied the dynamic SCGE model and comprehensively considered the four impacts of land use, capital investment, changes in transportation costs, and productivity, wherein they found that China's high-speed rail infrastructure construction has had positive impacts on regional economies. However, scholars have also indicated that the "polarization effect" caused by the construction of HSRs leads to the "reverse flow" of resources and elements, which is detrimental to the economic development of particular districts [21,22]. Furthermore, HSR construction also induces changes in the balance of regional economic patterns [23]. Based on different research fields and regions with different economic development levels, scholars have different research conclusions on the equity issues of HSR. At present, the academic community has not yet formed a unified research conclusion on the changes in regional balance brought about by high-speed railway. Yu and Yao [24] used the DID method and the Gini coefficient to measure the relationship between HSRs and income inequality; the study found that after HSR completion, the Gini coefficient of regional economies increased, and the income inequality in the region intensified. Wang and Zhang [25] found high-speed rail operation increases regional accessibility differences in the Central Plains Economic Region. It is also argued that HSR contribute to the formation of integration in regional development [26,27]. Bruzzone et al. [28] used the Gini coefficient and the coefficient of variation to find that the operation of the high-speed rail can make the distribution of the accessibility within the municipalities belonging to Susa Valley more balanced. Chen and Haynes [29] used a growth model following the standard Barro-type framework and found that HSR construction creates new locational advantages for impoverished areas through efficient railway services, thereby narrowing regional economic gaps at the national and regional levels.

In terms of research methods, at present, there are five main research methods used for research related to the spatial and economic effects of high-speed railways: comparative analysis, econometric model analysis, geographic information system (GIS) analysis, the index-based analysis method, and statistical and spatial analysis. 1. Comparative analysis method: the basic assumption of the comparative analysis method is that in addition to the factors to be studied, other factors in the control group and the experimental group are consistent or similar so as to study the differences in the various economic factors along the high-speed railway and non-high-speed railway. At present, the difference-in-differences method [8,24] and with-or-without comparison method [11] are widely used. The relative advantage of the difference-in-differences method is that it can eliminate the "noise" impact unrelated to the opening of high-speed railways and analyze the net effect of high-speed railway economic spaces. 2. Econometric model analysis: This method builds different econometric models to analyze the impact of one or more economic indicators on the high-speed railway and explore its impact mechanism. This method mainly constructs different models according to the research needs, such as the gravity model [7], the growth model [29], the structural equation model [19], and so on. 3. Geographic information system (GIS) analysis: This method uses GIS tools for data collection, data management and operation, spatial analysis, and network analysis and mapping to simulate or predict the economic impact of high-speed railways [8,30]. 4. Index-based analysis method: Some scholars try to use the method based on index analysis to explore the changes in spatial patterns and regional balance brought about by the opening of high-speed rail, such as the Gini index [31], accessibility level [32], economic potential [33], and so on. 5. Statistical and spatial analysis: This method is widely used in research relating to evaluating the impact of high-speed rail on regional economies and spatial patterns. Based on the geographic information system (GIS), Ortega et al. [34] used indicators, such as the accessibility level and Potential Accessibility Dispersion index, to measure the impact of high-speed rail on regional cohesion.

Nowadays, the content of research relating to HSRs has been gradually enriched, and the research perspectives are increasingly diversified. There is a growing body of literature focusing on the effects of HSRs on economic development and economic, spatial patterns, but there are few articles that combine them to produce a comprehensive understanding. As an important "one horizontal" of the "eight vertical and eight horizontal" passenger-dedicated line network proposed in China's "Medium and Long-Term Railway Network Planning", the Shanghai–Kunming HSR is a significant railway passage intended to connect the coastal, central, and inland regions of China. Because it is of strategic importance for the coordinated regional economic development of the Yangtze River Economic Belt and the economic drive along the Midwest, this paper focuses on the regions along the Shanghai–Kunming HSR by using GIS technology, spatial panel data models, and the entropy method to analyze the influence of regional economic development and spatial pattern. The research objectives are as follows.

(1) Utilize the DID model to quantitatively analyze the net effect of opening the HSR on the regional economic development along the route, excluding the influence of other factors;
(2) Analyze the characteristics and trends of the spatiotemporal evolution of the economic, spatial patterns by calculating the changes in the indicators of the economic, spatial pattern before and after opening the HSR;
(3) Use the entropy method to construct a comprehensive evaluation index system, measure the economic, spatial effect of the HSR and analyze the heterogeneity of the economic, spatial effect based on the difference in the level of economic development.

2. Materials and methods

2.1. The study area and data

The Shanghai–Kunming High-speed Railway (shown in Fig. 1) is a high-speed railway connecting Shanghai and Kunming City, Yunnan Province, running through the eastern, central, and western parts of China, forming an east–west traffic and economic belt. The Shanghai–Kunming HSR officially started construction in February 2009, with a total length of 2252 km. On December 28, 2016, the whole line of Shanghai–Kunming HSR was opened to traffic, marking the improvement of China's railway network and the establishment of the link between China's coastal, central, and inland regions, which has great socioeconomic significance.

The study areasselected in this paper are five provinces and one city along the Shanghai–Kunming HSR pathway (shown in Table 1), including Shanghai, Zhejiang, Jiangxi, Hunan, Guizhou, and Yunnan provinces, which cover an area of approximately 1.06 million km^2 and comprise 11% of the country's land area. There are considerable differences in the degree of economic development between the cities in

Fig. 1. The location of Shanghai–Kunming High-Speed railway.

the regions along the line, and the resources and natural endowment conditions vary from place to place. Since the area along the Shanghai–Kunming HSR is within the 11 provinces and cities of the Yangtze River Economic Belt, the regional economic impact of the Shanghai–Kunming HSR is of great significance to the balanced economic development of the Yangtze River Economic Belt, as well as the central region's rising strategy and the western development strategy. As of 2018, the total population of the region reached 28.1.38 million people, 20% of the total national population. Economically, the proportion of the region's total economic output in the country has gradually increased from 19.96% in 2008 to 20.98% in 2020. The coefficient of variation of the economic aggregate in the area along the Shanghai–Kunming HSR has also dropped from 0.57 in 2008 to 0.43 in 2020, indicating that the interprovincial economic development level in this region is gradually shrinking.

In this paper, relevant economic and social data from 2007 to 2018 at all prefecture levels in the provinces along Shanghai–Kunming HSR were selected for the study. Data related to the economic development of each city were collected from the 2007 to 2018 provincial statistical yearbooks on the China Economic and Social Big Data Research Platform (https://data.cnki.net/NewHome/index), and partially missing urbanization data were retrieved from the China Statistical Information Network (http://www.tjcn.org/tjgb/). The initial data of the shortest travel time between the cities were calculated by combining the "National Railway Train Timetable" of the corresponding years before (Appendix Table S1) and after the opening of the HSR (Appendix Table S2) and the data of the Ctrip travel APP. Coordinate data for the sites along the Shanghai–Kunming HSR were obtained from Google Maps (https://www.google.com/maps/).

This paper takes 62 prefecture-level-and-above cities across six provinces and cities along the Shanghai–Kunming HSR line as the research objects. Among them, there are 28 cities in the treatment group with stations along the Shanghai–Kunming HSR; the remaining 34 cities are in the control group.

2.2. Difference-in-differences model

In recent years, the difference-in-differences model has been widely used to evaluate the policy effects of public policies as well as large-scale projects [35–37]. The DID model effectively combines the presence-or-absence comparison method and the before-and-after comparison method and performs horizontal and vertical regressions. It divides the sample into a "treatment group" and a "control group" by whether or not a certain treatment is standard, which can effectively control the interference of other external factors other than the explained variables to some extent. While other control variables are often added to the model to further control for the effect of the "noise" present in the experimental and control groups in the natural experiments, more accurate estimators can be derived for the comparative effectiveness of the factors to be studied, enabling a more precise assessment of the net effect of policy actions so that more accurate estimators can be derived for the studied factors comparatively, enabling a more precise assessment of the net effect of policy actions.

In this paper, the DID model was used to investigate the regional economic effects of HSR construction, considering the opening of the HSR as a natural experiment, regarding 62 prefecture-level cities and six provinces and cities, including Shanghai, Zhejiang, Jiangxi, Hunan, and Guizhou of Yunnan, along a line of the Shanghai–Kunming HSR as study subjects, to explore the effects of the opening of the HSR on the regional economic development along the lines. The DID model is constructed as follows:

$$Y_{it} = \beta_0 + \beta_1 G_{it} + \beta_2 T_{it} + \beta_3 G_{it} \times T_{it} + X_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

In the formula, the subscript i of the variable represents each city along the Shanghai–Kunming high-speed railway line (i = 1, 2, …, n), and t represents the year. The explained variable of Y_{it} represents the economic development index of the city i in year t, which, according to the research objectives of this paper, includes the actual GDP, the actual GDP growth rate, the industrial structure upgrade index, and the urbanization rate. G_{it} is a regional dummy variable. T_{it} is a time dummy variable. The cross term of $G_{it} \times T_{it}$ is the dummy variable for HSR opening, and its coefficient β_3 is the value of the following DID, which is used to measure the magnitude of the net effect of HSR opening on the explained variables. X_{it} denotes the other control variables that affect the economic effects of HSR. α_i is a fixed effect, an unobservable individual characteristic. β_0 is a constant term. β_1, β_2, and β_3 are various coefficients, and ε_{it} is a random disturbance term. The descriptive statistics of each variable are shown in Table 2.

The idea of the industrial structure upgrade index among the explained variables is constructed with reference to the practices of Xu and Jiang [38], and the form is as follows:

Table 1
The economic situation of research area.

		2008	2012	2016	2020
		GDP (100 million yuan)	GDP (100 million yuan)	GDP (100 million yuan)	GDP (100 million yuan)
Provinces and cities along the HSR	Shanghai	14536.90	20181.72	29887.02	38700.58
	Zhejiang	21462.69	34665.33	47251.36	64613.00
	Jiangxi	6934.20	12948.88	18499.00	25691.50
	Hu'nan	11307.36	22154.23	31551.37	41781.50
	Guizhou	3504.48	6852.20	11776.73	17826.56
	Yunnan	6016.59	11097.39	16369.00	24521.90
Summary	Total	63762.22	107899.75	155334.48	213135.04
	nationwide	319516.00	540367.00	744127.00	1015986.00
	Proportion	19.96%	19.97%	20.87%	20.98%
	Coefficient of variation	0.57	0.51	0.46	0.43

Table 2
Variable descriptive statistics.

Variant names	Variable description	Average	Standard deviation	Max	Min
Actual GDP	Actual GDP logarithm	6.876	1.090	10.395	3.777
Actual GDP growth rate	(This year's actual GDP - last year's actual GDP)/last year's actual GDP	0.113	0.029	0.227	0.038
Industrial structure upgrade index	Proportion of primary industry × 1+Proportion of secondary industry × 2+Proportion of tertiary industry × 3	2.272	0.132	2.696	1.945
Urbanization rate	Urban resident population/ Permanent resident population	0.465	0.158	0.896	0.201
Time factor	$T_{it} = 1$ in the year after the HSR is opened, otherwise $T_{it} = 0$	0.281	0.449	1.000	0.000
Regional factor	$G_{it} = 1$ for cities along Shanghai-Kunming HSR, otherwise $G_{it} = 0$	0.452	0.498	1.000	0.000
HSR factor	If city i is a city along the Shanghai-Kunming HSR and HSR is opened, then $G_{it} \times T_{it} = 1$, otherwise $G_{it} \times T_{it} = 0$	0.136	0.343	1.000	0.000
Fixed asset investment	Fixed asset investment logarithm	15.769	1.075	18.528	12.402
Labor level	Number of urban employees at the end of the year/ total urban population at the end of the year	0.273	0.117	0.605	0.104
Road mileage	Road mileage logarithm	9.423	0.558	10.449	7.332
Extent of government intervention	Local government general fiscal revenue/city GDP	0.085	0.029	0.238	0.013

$$H = \sum_{i=1}^{3} c_i \times i = c_1 \times 1 + c_2 \times 2 + c_3 \times 3 \tag{2}$$

In the formula, ci represents the proportion of the i-th industry in terms of GDP, and the values of the industrial structure upgrade index of H range from 1 to 3. According to Petty Clark's theorem, the closer the index value is to 3, the better the development of the real estate industry, and the higher the level of industry.

This paper selects the following four control variables.

(1) Fixed asset investment: Fixed asset investment has always been an important tool for my country's macro-control. High-speed railway construction is a huge fixed asset investment, so it is very important to control the variable of fixed asset investment.
(2) Labor level: The agglomeration of the urban labor force can improve the technological level and stimulate local economic development. We divide the number of employed persons in cities and towns by the total urban population at the end of the year to reflect the labor level.
(3) Road mileage: The opening of a high-speed railway will cause a certain traffic substitution effect, so this paper uses the road mileage of each city as the proxy variable of traffic factors.
(4) Extent of government intervention: Regional economic output is usually affected by the degree of government intervention in economic activities. This paper selects the ratio of the local government's general fiscal revenue to the city's GDP as the control variable of the policy.

2.3. Research indicators

2.3.1. Accessibility level

Accessibility usually refers to the convenience of a certain place in a transportation system to reach a specific area, which is often used to evaluate the transportation network and traffic location. Among many accessibility level evaluation methods, weighted average travel time is a commonly used method [39], and its calculation formula is as follows:

$$A_i = \sum_{j=1}^{n} (S_{ij} \times M_j) \Big/ \sum_{j=1}^{n} M_j \tag{3}$$

In the formula, Ai is the accessibility level of the city i in the railway transportation network, and its value is negatively correlated with the level of accessibility. S_{ij} is the shortest travel time required to get from city i to city j in the railway transportation network; the unit is "hour". M_j refers to the social development level or the urban scale of city j, which is measured by using the actual GDP, with the unit of "100 million yuan". n is the sum of the number of cities along the Shanghai–Kunming high-speed railway after subtracting the i city.

2.3.2. Strength of interregional economic ties

The strength of interregional economic ties [40] represents the economic impact of the central city on the surrounding areas and the bearing capacity of the surrounding areas to the economic impact of the central city. It is usually measured by Newton's universal gravitation model. The specific construction formula is as follows:

$$L_i = \sum_{j=1}^{n} L_{ij} = \sum_{j=1}^{n} \left(\sqrt{P_i \times M_i} \times \sqrt{P_j \times M_j} \right) \Big/ D_{ij}^2 \tag{4}$$

In the formula, L_i represents the total amount of external economic ties of the city i. L_{ij} represents the strength of economic ties between city i and city j. P_i and P_j represent the population size of city i and city j, in "ten thousand people". M_i and M_j are the social development level or urban scale of city i and city j, which are measured by using the actual GDP, with the unit of "100 million yuan". D_{ij} refers to the shortest time distance between node city i and node city j of the railway transportation network, with the unit of "minutes".

2.3.3. Economic potential

Different from the dual economic relationship between the cities calculated using the gravity model, economic potential [41] is used to calculate the comprehensive interaction force between a city and surrounding cities from the perspective of the total amount. The specific calculation formula is as follows:

$$O_i = \sum_{j=1}^{n} \frac{M_j}{S_{ij}^{\mu}} \times 10^{-4} \tag{5}$$

In the formula, O_i is the value of the economic potential of city I, and μ is the friction coefficient, which is generally 1.

2.3.4. Coefficient of variation

The coefficient of variation [26] is used to analyze the dispersion of data, and its calculation method is as follows:

$$CV = \frac{SD}{MN} \tag{6}$$

$$CV' = \sqrt[3]{CV_{A_i} \times CV_{L_i} \times CV_{O_i}} \tag{7}$$

Where SD is the standard deviation and MN is the average. CV_{Ai}, CV_{Li}, and CV_{Oi}, are the variation coefficients of the accessibility level, total external economic ties, and economic potential, respectively. CV' is a comprehensive coefficient of variation that combines the level of accessibility, economic potential, and the t total external economic ties.

2.3.5. Moran's I index

The Moran's I index [42] can measure the agglomeration features of regional economies as a whole, and a value greater than 0 indicates that the regional economic development has a spatial positive correlation, less than 0 indicates that the regional economic development is a spatial negative correlation, and equal to 0 indicates that no spatial correlation exists for regional economic development. The Moran's I index was calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{8}$$

In the formula, x_i and x_j denote the total actual GDP of city i and city j, respectively, and ω_{ij} is the spatial weight matrix.

2.3.6. Theil coefficient

The Theil coefficient [43] is an indicator used to measure the difference in the level of economic development between regions, and is calculated in this paper as GDP-weighted specific gravity, which is calculated as follows:

$$T = \sum_{i=1}^{n} y_i \lg \frac{y_i}{p_i} \tag{9}$$

In the formula, y_i is the ratio of the GDP of city i to the total GDP of the sample city, and p_i is the ratio of the total population of city i to the total population of the sample city. The smaller the Theil coefficient, the smaller the difference in the level of regional economic development.

2.3.7. Comprehensive index

Fig. 2 shown the technical route of the research. In order to objectively estimate the comprehensive impact of HSR opening on regional eco spatial effects in regions with different degrees of economic development, in this paper, the entropy value method is used to determine the weights and construct a comprehensive evaluation system for regional eco spatial effects of HSR (shown in Fig. 2). First, we construct an evaluation index system of the impact of HSR on regional economic development based on the did coefficients of actual GDP, actual GDP growth rate, industrial structure upgrade index and urbanization rate in regions with different degrees of economic development. Then, calculate the growth rate, promotion multiple and promotion multiple of regions with different degrees of economic development, respectively, and take the standardized value of the multipliers of the three as the evaluation index of the impact of HSR on the regional economic, spatial patterns. Finally, the two indicators are integrated to obtain the comprehensive score that can measure the regional economic, spatial effects of HSR in different degrees of economic development. According to the requirements of the entropy method, the original issue needs to be standardized first. The specific calculation formula is as follows:

$$E_i = w_1 GDP_i + w_2 iGDP_i + w_3 H_i + w_4 U_i \tag{11}$$

$$K_i = A_i \times L_i \times O_i \tag{12}$$

$$F_i = w_5 E_i + w_6 K_i \tag{13}$$

In the formula, E_i is the evaluation index score of the impact of HSR on regional economic development. K_i is the evaluation index score of the impact of the HSR on the regional economic, spatial pattern. F_i is the comprehensive score of the regional economic, spatial effect. w_1, w_2, w_3, and w_4 are the weights of the DID coefficients of the standardized actual GDP, actual GDP growth rate, industrial structure upgrading index, and urbanization rate, respectively. w_5 and w_6 are the evaluation index scores of the impact of HSR on regional economic development and economic, spatial pattern.

3. Results

According to the DID model established above, in this section, we mainly used Stata 15.2 software [44], which measures the impact of economic development along a line area of HSR opening from three aspects: the economic growth effect, industry structure change effect, and urbanization level impact effect and conducts a discussion of heterogeneity.

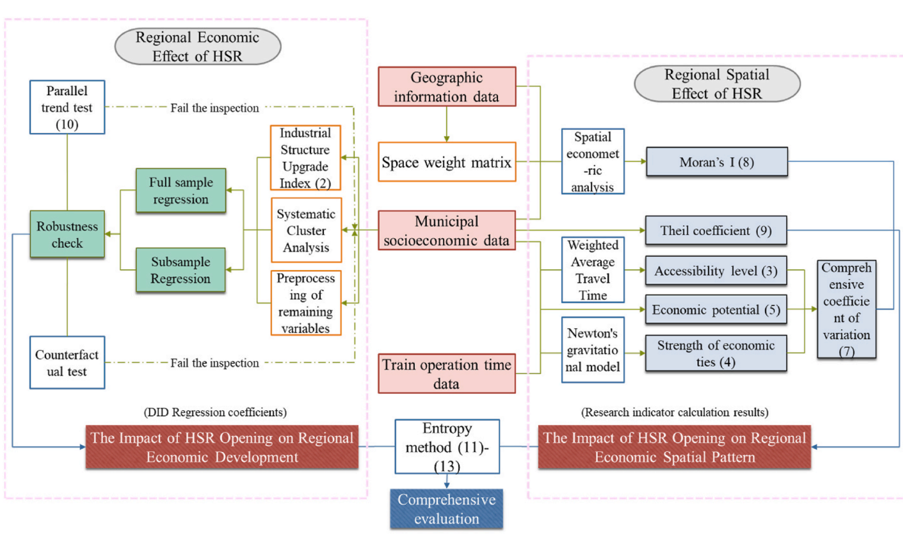

Fig. 2. Technical research route.
Note: The numbers in parentheses represent the formulas used in the process.

3.1. Regional economic development effects

3.1.1. Full sample regression analysis

Table 3 shows the full sample difference-in-differences model regression results. The regression coefficients Diff (Before) and Diff (After) show the average levels of actual GDP, actual GDP growth rate, industrial structure upgrade index, and urbanization rate before and after the HSR opening in the treatment and control groups, respectively. From the results in the table, it can be seen that before the opening of the Shanghai–Kunming HSR, there was no significant difference in the average levels of actual GDP, industrial structure upgrading index, and urbanization rate between the treatment group and the control group. In model (2), the regression coefficient of Diff (Before) reaches a significant level of 1%, indicating that there is a significant difference in the average level of actual GDP growth rates between the treatment group and the control group before the opening of the Shanghai–Kunming HSR. However, the regression coefficients of models (1), (3), and (4) Diff (After) are all significant at the level of at least 5%, indicating that the average levels of actual GDP, industry structure upgrade index, and urbanization rate gradually differ between the treatment and control groups after the opening of the HSR. From the fitting situation, the R^2 of the four models are all above 0.35, and the fitting effect is good.

The coefficient of DID is used to measure the real policy effect of the HSR opening on the explained variables, and it is an important variable in this paper to examine the effect of HSR opening on the economic development of regions along the line. The regression coefficient for DID in the model (1) is significantly positive at the 1% level, indicating that the opening of an HSR has a significant enhancing effect on the total amount of GDP in regions along the HSR relative to regions that have no HSR. The regression coefficient of DID in the model (2) is significantly negative at the level of 5%, indicating that the opening of the Shanghai–Kunming HSR will lead to a slowdown in the economic growth rate of the areas along the line, and the boosting effect on the total economic volume in the region along the line will gradually diminish, which coincides with the national macroeconomic trend. In model (3), the regression coefficient of DID is significantly positive at the level of 10%, indicating that the opening of the Shanghai–Kunming HSR can significantly promote the optimization and upgrading of the industrial structure along the line compared with the areas where the HSR has not been opened, but the significance of this effect is not obvious, and there is still much room for improvement in terms of the industrial structure. The DID coefficient in model (4) has a positive significance at the level of 1%, indicating that the construction of the HSR accelerates the flow of population between regions, promotes the flow of rural population to cities, and changes the population layout of cities, which plays an important role in promoting urbanization process in China.

3.1.2. Subsample regression analysis

To verify the heterogeneity of the regional economic effects resulting from the opening of the HSR, the full sample was divided into three subsets, including economically developed, less economically developed, and economically lagging regions. The subsamples were subjected to difference-in-differences model regression. Per capita GDP is an internationally recognized indicator for evaluating the level of regional economic development [45]. Based on the per capita GDP indicators of the provinces and cities along the Shanghai–Kunming HSR, according to the results of the SPSS24.0 software system cluster analysis [46], the regional economic development level was defined and evaluated. The estimated results are shown in Table 4.

As can be seen in the table, even if different levels of economic development are distinguished, the correlation between the opening of an HSR and the four explained variables of actual GDP, actual GDP growth rate, industrial structure upgrade index, and urbanization rate in the subsample is still similar to that in the whole sample (see Table 5). The difference is that for regions with different levels of economic development, the net effect of the opening of HSR policies has certain heterogeneity.

3.1.3. Parallel trend test

The important premise of using the DID model to estimate the impact of the opening of the HSR on the area along the line is that the treatment and control groups satisfy the parallel trend assumption; that is, it requires that both the treatment and control groups maintain the same change trend before the opening of the HSR. Therefore, based on the DID model, a parallel trend test model was constructed to test the dynamic effect of HSR opening as follows:

$$Y_{it} = \beta_0 + \beta_1 G_{it} + \beta_2 T_{it} + \beta_t \sum_{n-t}^{n+t} G_{it} \times T_{it} + X_{it} + \alpha_i + \varepsilon_{it} \tag{10}$$

Of the formula, Tit is the year when the HSR was opened and is tested in this paper four years before and after the year when the HSR was opened. The cross term of $G_{it} \times T_{it}$ is the dummy variable of opening the HSR, and the coefficient β_t of the cross term is not significant in the years before opening the HSR, indicating that the treatment group and the control group satisfy the parallel trend assumption. Estimates of regression coefficients of dummy variables for HSR opening at each year are shown in the figures, and the dashed lines indicate 95% level confidence intervals. As shown Fig. 3, the regression coefficients of the dummy variables for HSR opening from the results of the four parallel trend tests were not significant before HSR opening, satisfying the parallel trend assumption.

Table 3
Regression results of full sample DID model.

		Actual GDP	Actual GDP growth rate	Industrial structure upgrade index	Urbanization rate
		(1)	(2)	(3)	(4)
Before the opening of HSR	Control	−8.843	0.188	2.091	−0.345
	Treated	−8.848	0.198	2.095	−0.338
	Diff (Before)	−0.006 (-0.16)	0.010***(4.70)	0.003 (0.38)	0.007 (1.15)
After the opening of HSR	Control	−9.084	0.166	2.118	−0.367
	Treated	−8.868	0.168	2.149	−0.331
	Diff (After)	0.216***(3.92)	0.001 (0.38)	0.031**(2.27)	0.036***(3.74)
	DID	0.222***(3.47)	−0.009**(-2.30)	0.028*(1.75)	0.029***(2.59)
Control variable	Lnasset	0.970***(53.28)	−0.008***(-7.52)	0.066***(14.64)	0.126***(39.40)
	Labor	0.062 (0.47)	0.008 (0.96)	−0.146***(-4.47)	0.001 (0.03)
	Government	−0.612 (-1.17)	0.006 (0.19)	0.738***(5.71)	0.128 (1.39)
	Highway	0.053*(1.85)	0.006***(3.45)	−0.095***(-13.27)	−0.125***(-24.70)
	Year effect	Control	Control	Control	Control
	Area effect	Control	Control	Control	Control
	N	736	736	736	736
	R^2	0.88	0.36	0.49	0.80

Note: *p < 0.05, **p < 0.01, and ***p < 0.001.

Table 4
Regression results of sub-sample DID model.

		Actual GDP	Actual GDP growth rate	Industrial structure upgrade index	Urbanization rate								
		Economically developed (5)	Economically undeveloped (6)	Economically backward (7)	Economically developed (8)	Economically undeveloped (9)	Economically backward (10)	Economically developed (11)	Economically undeveloped (12)	Economically backward (13)	Economically developed (14)	Economically undeveloped (15)	Economically backward (16)
Before the opening of HS	Control	−8.561	−9.005	−7.802	0.223	0.251	0.091	1.347	2.188	2.578	−0.297	−0.534	−0.170
	Treated	−8.592	−9.036	−7.772	0.228	0.266	0.099	1.347	2.158	2.581	−0.270	−0.505	−0.184
	Diff (Before)	−0.031 (-0.37)	−0.031 (-0.55)	0.029 (1.04)	0.005 (0.53)	0.015*** (3.87)	0.008*** (2.73)	−0.000 (-0.00)	−0.030** (-2.51)	0.003 (0.26)	0.027 (1.49)	0.028**(2.49)	−0.013** (-2.15)
After the Opening of HS	Control	- 8.684	−9.301	−7.841	0.202	0.232	0.074	1.325	2.200	2.643	−0.323	−0.560	−0.147
	Treated	- 8.622	−9.167	−7.761	0.202	0.234	0.074	1.383	2.186	2.652	−0.288	−0.524	−0.138
	Diff (After)	0.062 (1.08)	0.134 (1.61)	0.080 (1.49)	0.000 (0.03)	0.003 (0.50)	0.001 (0.12)	0.059*** (4.57)	−0.014 (0.77)	0.009 (0.41)	0.035*** (2.74)	0.036**(2.14)	0.009 (0.77)
	DID	0.093 (1.03)	0.165*(1.72)	0.051 (0.85)	−0.005 (-0.50)	−0.012* (-1.82)	−0.007 (-1.16)	0.059*** (2.93)	0.017 (0.80)	0.006 (0.25)	0.008 (0.39)	0.008 (0.41)	0.022*(1.71)
Controlvariablerowhead	Lnasset	0.554*** (14.16)	0.895*** (26.75)	0.680*** (31.71)	−0.009** (-2.00)	−0.015*** (-6.13)	−0.014*** (-6.29)	0.033*** (3.84)	0.061*** (8.41)	0.043*** (4.80)	0.058*** (6.69)	0.121*** (18.01)	0.080*** (16.90)
	Labor	−0.968*** (-4.09)	−0.522*** (-2.60)	0.556*** (5.13)	−0.017 (-0.66)	0.036**(2.52)	−0.014 (-1.32)	−0.098** (-1.86)	−0.388*** (-8.97)	−0.047 (-1.04)	−0.019 (-0.35)	−0.016 (-0.39)	0.017 (0.73)
	Government	9.206*** (13.20)	−4.558*** (-4.60)	−2.678*** (-6.30)	−0.127* (-1.67)	0.012 (0.17)	0.075*(1.74)	1.587*** (10.22)	1.507*** (7.07)	0.282 (1.58)	1.740*** (11.25)	0.135 (0.68)	−0.248** (-2.65)
	Highway	0.758*** (15.62)	0.262*** (4.47)	0.396*** (9.89)	0.005 (1.03)	0.009**(2.14)	0.024*** (6.00)	0.039*** (3.60)	−0.089*** (-7.10)	−0.110*** (-6.56)	−0.021* (-1.94)	−0.095*** (-8.07)	−0.070*** (-7.88)
	Year effect	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control
	Area effect	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control
	N	108	235	393	108	235	393	108	235	393	108	235	393
	R^2	0.97	0.88	0.93	0.43	0.46	0.30	0.86	0.57	0.24	0.83	0.72	0.63

Note: $^*p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

Table 5
Increase in spatial efficiency indicators.

	Accessibility level	Total economic ties intensity	Economic potential
Economically developed areas	45.76%	15.63	5.34
Economically underdeveloped areas	51.00%	38.49	7.99
Economically backward areas	56.04%	62.69	10.06

3.1.4. Counterfactual testing

The placebo test, also known as the counterfactual test, by setting a spurious event is an important approach to testing the robustness of DID model. To further verify the validity of the results, the robustness test is performed in this paper by replacing the time point of the HSR opening. The test results are omitted. After replacing the time point of the HSR opening, none of the DID coefficients of model (1)–model (4) were significant, and the robustness test passed, confirming the validity of the regression results from the DID model.

3.2. Characteristics of spatiotemporal evolution of economic spatial patterns along HSR

3.2.1. Evolutionary characteristic indicator

The HSR elevate accessibility levels in cities along the line through a 'spatiotemporal compression' effect. Increased accessibility levels, which reduce the time cost for residents to travel and corporate transport, enable a more frequent movement of productive factors, stronger regional economic linkages, and altered locational advantages, which in turn affect regional economic, spatial patterning. Therefore, this paper selected 28 cities with stations along the Shanghai–Kunming HSR to analyze the spatial and temporal evolution of the economic and spatial patterns.

From the perspective of the accessibility level, the spatial pattern of accessibility along the Shanghai–Kunming HSR is centered on the eastern cities and gradually radiates to the central and western cities, showing a spatial pattern of high in the eastern coastal areas and gradually decreasing in the inland areas of the central and western regions (shown in Fig. 4 a, 4.b, 4.c). Due to the influence of geographical location and HSR network density, Kunming, Qujing, Southwest Guizhou, and other places in the west receive less "space-time compression" of HSR, and the accessibility level is poor. Before the opening of the high-speed railway, the accessibility level of cities along the Shanghai–Kunming high-speed railway was in the range of 4.62 h–21.73 h. After the opening of Shanghai–Kunming HSR, the accessibility spatial pattern of cities along the line has not changed greatly, but the accessibility level of cities with stations along the line has been improved to varying degrees, and the growth rate has reached more than 40%. Because of the influence of external environmental factors such as site level, there are certain differences in the degree of accessibility improvement in each city. The accessibility growth rate of inland areas in the Midwest is significantly higher than that of the eastern coastal areas. Among them, Qianxinan Buyi and Miao Autonomous Prefecture have the highest growth rates of accessibility level, reaching 70.21%.

In terms of the intensity of total economic ties, the spatial distribution of the total economic ties intensity of the cities along the Shanghai–Kunming HSR is high in the eastern coastal areas and low in the inland areas, which is in line with the distribution of accessibility levels (shown in Fig. 4 d, 4.e, 4.f). There are significant differences in the total strength of urban economic links, mainly due to the eastern regions having a higher density of HSR networks, stronger economic foundations, and a more frequent flow of economic factors, while the central and western regions are limited by transportation infrastructure, geographical location, terrain, and other factors, and the flow of economic factors is blocked and the intensity of economic ties is not high. After the opening of the Shanghai–Kunming HSR, the strength of the economic ties of the cities with stations along the line has increased in a visible range, with an average increase of 49 times. Among them, the strength of the economic ties of Qianxinan Prefecture and Liupanshui City has increased by a multiple of 248.41 times and 174.51 times, respectively. The range of total economic ties intensity of cities along the

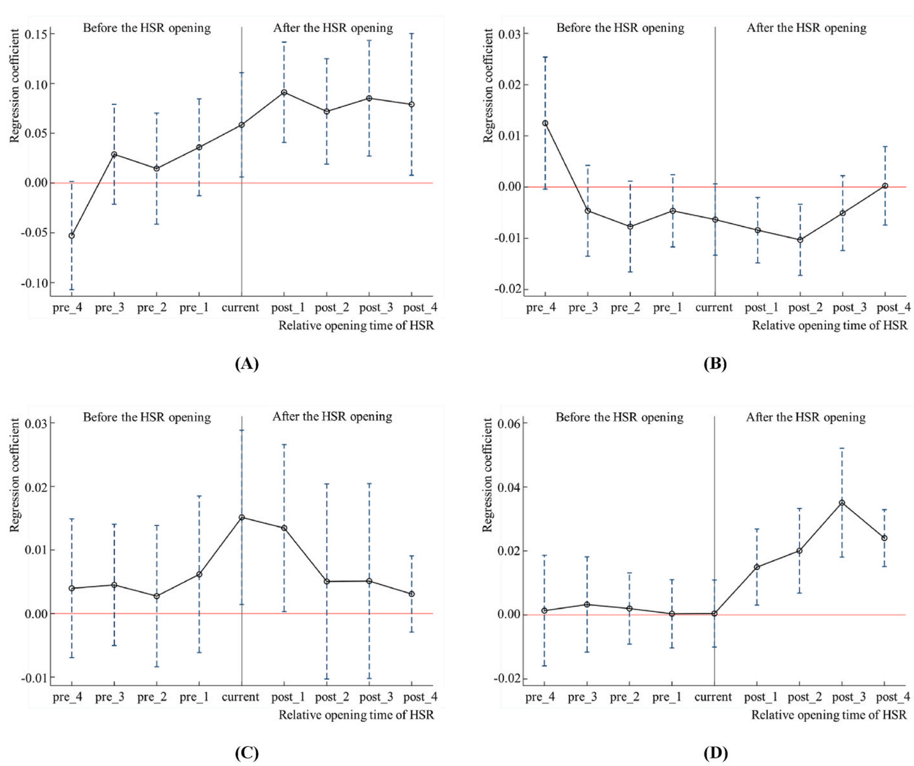

Fig. 3. Parallel trend test results of actual GDP (**A**), actual GDP growth rate (**B**), industrial structure upgrade index (**C**), and urbanization rate (**D**).

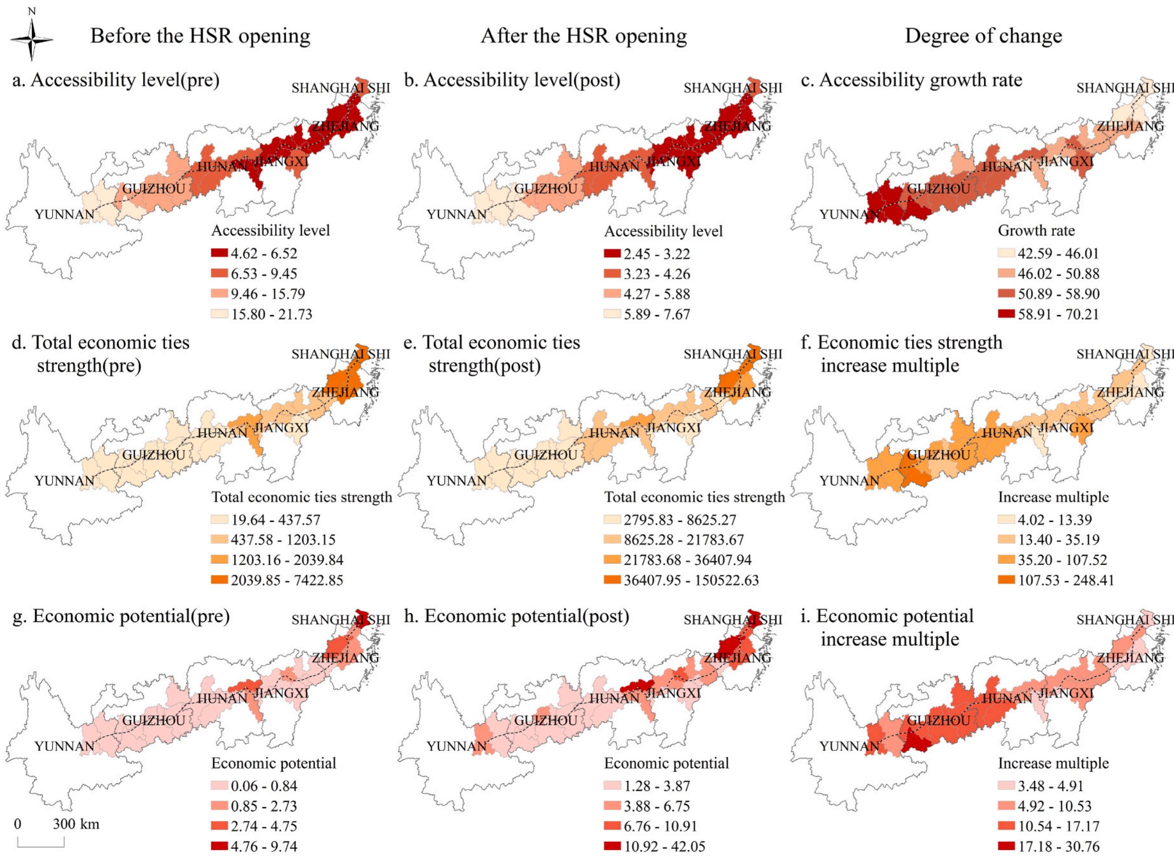

Fig. 4. Changes in the spatial pattern of evolution characteristic indicators.

Shanghai–Kunming High-speed Railway has increased from 19.64 to 7422.85 to 2797.83–150522.63; the growth has a visible improvement. The opening of the HSR has shifted the center of the total strength of the economic ties of the cities in the region to the west, which has driven the development of the central and western regions and improved the overall economic vitality of the region.

In terms of economic potential, as China's economic center, Shanghai has always been in first place before and after the Shanghai–Kunming HSR opening due to its good transportation foundation and solid economic strength, which play important roles in radiating and driving the surrounding cities (shown in Fig. 4 g, 4.h, 4.i). Before the opening of the high-speed rail, the overall regional economic potential was at a low level, and there were few high-value points of economic potential. After the opening of HSR, the high-value points of regional economic potential have increased significantly. However, the economic potential of western cities is still at a low level in the region. After the HSR opening, the space-time distance from Hangzhou and Changsha, the second and third cities with economic potential, to other cities, have significantly shortened and their economic potential greatly have improved, becoming a new growth pole for regional economic development. At the same time, Guiyang and Kunming, located in the west, have gradually demonstrated their radiation force on surrounding cities. Although the opening of an HSR can significantly enhance the economic potential of cities along the line, there are specific regional differences, showing a trend of uneven growth. On the whole, the change range of the economic potential of the western cities of the corridor is greater than that of the central cities and greater than that of the eastern cities. After the HSR opening, Hangzhou, Changsha, Guiyang and Kunming, which have gradually emerged as high-value points of regional economic potential, still have a good range of economic potential improvement and rapid development momentum.

Judging from the perspective of accessibility level, the strength of total economic ties, and economic potential growth, it can be seen that the economically backward areas are greater than economically underdeveloped areas than economically developed areas, which is mainly due to the differences between the transportation infrastructure in various regions.

From the perspective of the coefficient of variation, the coefficient of variation of the accessibility level and economic potential of the areas along the Shanghai–Kunming HSR has decreased after the opening of the HSR, indicating that the gap in the accessibility level and economic potential between cities has decreased, and the spatial diffusion effect has been enhanced. However, the coefficient of variation of the strength of economic ties increased slightly after the HSR was opened, and the coefficients of variation (Table 6) were all greater than 1, indicating that there were still large differences in the economic ties strength in this region and the gap in the total economic ties strength between cities increased slightly. Judging from the comprehensive coefficient of variation, after the opening of the Shanghai–Kunming HSR, the comprehensive coefficient of variation dropped from 1.098 to 0.900 (Table 6). It shows that in the area along the Shanghai–Kunming HSR, the diffusion of space and the agglomeration of economic elements occur at the same time, and the diffusion is the main effect. The radiation of the economic growth pole drives the development of surrounding cities, the Matthew effect is weakened, and the regional economic, spatial pattern presents a state of balanced development, which is conducive to the formation of regional economic integration.

3.2.2. *Moran's I index and Theil coefficient*

Moran's I index and Theil coefficient are used to measure the agglomeration characteristics of regional economic space and the difference of economic development level along the Shanghai–Kunming HSR (Fig. 5). From the perspective of the global autocorrelation index, the Moran's I index from 2007 to 2018 passed the significance level test

Table 6
Coefficient of variation.

	accessibility level coefficient of variation	Total economic ties intensity coefficient of variation	Economic potential coefficient of variation	Comprehensive coefficient of variation
Before the opening of HSR	0.550	1.514	1.590	1.098
After the opening of HSR	0.373	1.536	1.273	0.900

of 1%, and its value fluctuated around 0.100, indicating that the regional economic space along the line has the characteristics of weak agglomeration and certain spatial dependence of economic development, and the characteristics of regional economic, spatial agglomeration do not change significantly before and after the opening of the HSR. From the overall difference in the regional economic development levels, the Theil coefficient showed a gradual downward trend from 2007 to 2018. The Theil value decreased significantly from 0.320 in 2007 to 0.189 in 2018, indicating that the gap between the economic development level of the region is gradually decreasing and the regional economic development tends to be balanced.

3.3. Comprehensive index measurement

Based on the regression results of the sub-sample double difference model and the improvement range of spatial indicators of different economic development levels, it is calculated by using the entropy method, w1 = 0.22, w2 = 0.21, w3 = 0.34, w4 = 0.23, w5 = 0.43, w6 = 0.57 in formula (11)-(13). The calculation results of the evaluation index were shown Table 7.

Judging from the index score of the impact of the HSR on regional economic development and spatial patterns, the opening of the HSR plays a positive role in the comprehensive level of economic development of regions with different economic development levels and has heterogeneity. From the score of the E_i index, it can be seen that the HSR plays a significant role in promoting the economic development of economically underdeveloped areas and developed areas, especially for economically underdeveloped areas, while for economically backward areas, this positive impact is relatively weak. This is mainly because the "space-time compression" effect produced by the opening of the HSR greatly shortens the space–time distance between cities, which is conducive to the increased flow rate of labor, capital, technology, and other production factors among regions, resulting in "polarization effect" and "diffusion effect". Due to the "polarization effect", production factors will flow from the surrounding areas with low marginal return and poor economic growth environment to the central areas with high marginal return and good economic growth environments. At the same time, the talent flow brought by the HSR opening makes it easier for intellectual capital to break through the space constraints so as to improve the technological innovation ability of backward areas. Coupled with the

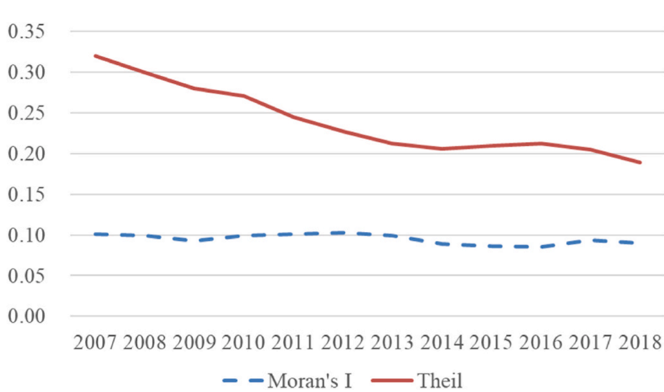

Fig. 5. Moran's I index and Theil coefficient.

Table 7
Evaluation index score.

	Economically developed areas	Economically underdeveloped areas	Economically backward areas
E_i	0.035	0.040	0.016
K_i	0.142	0.256	0.405
F_i	0.096	0.163	0.238

law of diminishing marginal returns, production factors will also overflow from the central area to the surrounding areas. Under the joint action of the two effects, the economically underdeveloped areas have obtained greater advantages and interests, which is a better choice of production factors. For economically backward areas, the area has large topographic undulations, the geographic cost of HSR construction is high, and the required HSR construction techniques are high, so that the HSR opening time is later than that in the central eastern region, and the economic effects of HSR cannot be fully manifested in the short term.

The opening of an HSR also has positive externalities, which can make the economic ties between regions closer, and the central region has a more significant economic driving effect on the surrounding regions. It can also be seen from the score of K_i that the positive effect of the HSR on the economic, spatial pattern of economically backward areas is the most significant, which means that the accessibility level, the strength of economic ties, and economic potential of economically backward areas improved the most significantly, which is conducive to attracting the aggregation of knowledge capital and knowledge-intensive industries so as to improve the local economic development level.

In the comprehensive evaluation system of the regional economic, spatial effect of the HSR, the scores of economically backward areas, economically underdeveloped areas, and economically developed areas decrease in turn. It can be seen that in the long-term development, with the improvement of the regional advantages of economically backward areas and economically underdeveloped areas, production factors such as talent and capital in economically developed areas will shift to these areas, which will drive the level of economic development in these regions, narrow the economic development gap between the entire regions, and be conducive to the balanced development of regional economies and the realization of regional economic integration.

4. Discussion

4.1. Feasibility of the proposed workflow

From the perspective of economy and space, this paper measures the economic, spatial effect of the HSR by studying the impact of the opening of a HSR on the regional "economic development" and the "evolution of the economic spatial pattern" along the line. On the basis of previous research, this paper comprehensively evaluates the economic and spatial effects of the HSR considering different levels of economic development and enriches the research on the cross-regional impact of the HSR. The method proposed in this paper is thorough, and all the selected indicators can be quantitatively analyzed, taking into account the two dimensions of time and space and synthetically evaluating the economic, spatial effect of the HSR based on the level of economic development, which can assist the government in planning and decision-making. The method proposed in this study is also applicable to other HSRs.

4.2. Heterogeneity of HSR economic spatial effects

It can be seen from the above experimental results that there is clear regional heterogeneity in the impact of Shanghai-Kunming HSR opening on regional economic, spatial development with different degrees of economic development. In terms of the economy, the main influencing factors were analyzed as follows.

(1) Industrial structure: The HSR have a positive impact on the optimization of industrial structure in regions with different levels of economic development. Among them, economically developed areas have higher industrial optimization effects, followed by economically underdeveloped areas, while economically backward areas have the smallest industrial structure optimization effect. This phenomenon verifies the "siphon effect" resulting from HSR construction, whereby economic elements such as capital and technology are clustered towards the central region, which in turn accelerates the optimization of upgrading industrial structures in the central region.

(2) Urbanization rate: Among the effects of the urbanization process, the opening of the Shanghai–Kunming HSR has a more significant effect on the level of urbanization in economically backward areas, while the positive effect on economically developed and economically underdeveloped areas is not significant. This may be due to the high level of urbanization in economically developed and underdeveloped areas, while economically backward areas have a poorer level of urbanization.

(3) Economic aspects: The industrial structure optimization and population aggregation brought by the HSR can improve the productivity of the regions along the line, which is ultimately reflected in the improvement of the total economic volume. In terms of economic growth, the opening of HSRs has a certain negative impact on economic growth, which is also consistent with the research conclusion of Wang and Nian [47]. This is probably because HSRs are characterized by high costs and long payback periods, which in turn cause the local government to miss the opportunity cost of developing other industries. From the perspective of heterogeneity, HSRs have a significant level of 10% on the economic aggregate and growth rate of economically underdeveloped regions, while the negative impact on economically developed and economically backward regions is not significant.

From the benchmark regression results of the full sample, the opening of the Shanghai-Kunming HSR has a significant positive effect on economic aggregate, industrial structure upgrading and urbanization rate. However, from a regional perspective, for economically developed regions, the opening of the HSR can significantly promote the upgrading of the industrial structure in economically developed regions but has no significant impact on the economic aggregate and urbanization rate. The reason is that the opening of the HSR has promoted the circulation of production factors. Through the siphon effect, production factors flow to economically developed areas to promote the upgrading of the local industrial structure. However, economically developed areas have a solid economic foundation and a high urbanization rate, so the introduction of the HSR has no significant effect on their urbanization rate and economic aggregation. The opening of the HSR can further improve the accessibility level, economic ties strength and economic potential of economically developed areas, but the increase is less than that of economically underdeveloped areas and economically backward areas, mainly because economically developed areas have relatively complete infrastructure before the opening of HSR. Transportation infrastructure and communication with the surrounding areas are more convenient. For economically underdeveloped regions, the opening of the HSR can significantly promote increased economic aggregate, but it has no significant impact on the upgrading of industrial structure and urbanization rate. The level of accessibility, the strength of economic ties, and the economic potential of economically underdeveloped regions are also in the middle, which is in line with expectations. For economically backward areas, the opening of the HSR has improved the local urbanization level at a significance level of 10% but has no significant impact on economic aggregation and industrial structure upgrades, the overall economic effect of the HSR opening is smaller than in the other two regions. In the short term, the economic effect of the HSR is not significantly reflected, but from the perspective of spatial pattern, the degree of improvement in the accessibility level, economic ties strength and economic potential of economically backward areas exceeds that of economically developed and economically underdeveloped areas.

Although the economic effect of the HSR in economically backward areas is the least significant, the opening of the HSR has obvious heterogeneity in terms of the spatial effect, which greatly improves the accessibility level, strength of economic ties, and the economic potential of economically backward areas. As a whole, economically backward regions have higher economic space effect and have more significant posterior predominance. With the improvement of the regional advantages of economically backward and economically underdeveloped areas, administrative barriers will be gradually eliminated, which is conducive to the migration of knowledge industries and knowledge investments in economically developed areas to these areas, as well as people's living and employment, so as to stimulate the economic development of economically backward and economically underdeveloped areas and achieve the balanced development of regional economies.

4.3. Limitations and implications

There are still some deficiencies in this study: ①Due to the staggered existence of HSRs, the research object will be affected by other HSRs except the Shanghai–Kunming HSR, and there is a certain spatial overlap effect, which may lead to deviations in the research results. ② In this paper, the DID model was used to estimate the economic effect of opening the Shanghai–Kunming HSR on the areas along the line compared with the areas along the non-Shanghai–Kunming HSR, but it cannot accurately quantify the specific value. ③ Due to the short service life of Shanghai–Kunming HSR, the impact on the regional economic development along the line has not been fully revealed, and the long-term impact of the opening of HSR on the areas along the line needs to be further studied. ④Due to the availability of data, it is difficult to collect micro-data such as railway ticket prices and passenger numbers completely. Therefore, this paper only analyzes the economic space effect of the HSR at the macro level. If micro-data can be used to analyze demand elasticity, it will make this research more complete. ⑤The generation of time-scaled map based on travel time [48–50] is an excellent visual method to analyze the spatiotemporal compression effect of HSR, which is also one of our future research directions.

Unlike existing studies on regional economy and space of high-speed rail, this paper uses a multi-period double-difference model to explore the economic impact of cross-regional high-speed rail. According to the results of cluster analysis, group regression is performed on three regions with different economic development levels to explore the heterogeneity of the economic effect of high-speed rail. At the same time, this study proposes an objective comprehensive analysis framework that combines the regional economic effects of high-speed rail with the regional spatial effects of high-speed rail to measure the comprehensive economic and spatial effects of the opening of high-speed rail on regions with different levels of economic development. This study will provide a reference for the research on the cross-regional economic spatial impact of high-speed rail.

5. Conclusions

Based on the data related to social economy and train running times along the Shanghai–Kunming HSR from 2007 to 2018, this paper uses GIS technology, spatial panel data models, and the entropy method to estimate the direct impact of HSRs on the spatial patterns of regional economic development along the route. The conclusions of this paper are as follows:

Although the HSR opening has a limited effect on increasing the economic growth rate, the HSR plays a positive role in the economic development of the regions along the line. Due to the changes in the economic spatial pattern caused by the HSR opening, the regions along the line have changed from a single-growth pole to a multi-growth pole, radiating together to drive the economic development of surrounding cities. In addition, the impact of the HSR opening on the regional economic development and spatial pattern along the line exhibits significant heterogeneity. In the long run, production factors, such as talent and capital in economically developed areas, will shift to areas with relatively backward economies. The HSR opening will narrow the economic development gap between the entire region and promote the balanced development of regional economies.

In general, the method proposed in this study is comprehensive and suitable for other HSRs or regions. The results will be beneficial to site selection, industrial layout, urban planning, and so on.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seps.2023.101583.

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