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Research Article

The Impacts of High-Speed Railway on Urban GDP and Its Agglomeration: Evidence from China

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This study develops difference-in-differences (DID) models to examine the direct and indirect effects of high-speed railway (HSR) operation on the urban gross domestic product (GDP) and its agglomeration. The period from 2010 to 2019 is selected as the study period, and 30 HSR-operating cities across the Chinese mainland are chosen as the study sites to be investigated. Individual fixed effects and time fixed effects are introduced to panel data models to account for the heterogeneities between cities and the endogeneities of explanatory variables. Estimation results suggest that the operation of HSR can improve the development of the urban GDP by accelerating the migration of population to HSR-operating cities, promoting the upgrading of the urban industrial structure, and improving the level of urban scientific research. Moreover, the level of urban economic agglomeration can also be improved as a result of HSR. However, the ability of HSR-promoting economic development is more significant in cities with more developed economies. Therefore, when formulating a sensible plan for the development of HSR, policymakers should prioritize the construction of HSR in more developed cities.

1. Introduction

High-speed railways (HSR) have earned widespread recognition as a fast, safe, and comfortable intercity transportation mode [1]. This transit form significantly improved the overall travel satisfaction for passengers [2, 3]. Over the past decade, the mainland of China has witnessed a notable surge in the development of HSR. As of the end of 2019, China possesses the world's most extensive HSR network, encompassing an operational distance exceeding 35,000 billion kilometers [4].

Concurrently, the rapid expansion of HSR has ignited a surge of scholarly investigations worldwide into the spillover effects generated by this transportation mode [5–7]. A profound understanding of the economic externalities associated with HSR is paramount, as it empowers us to conduct a comprehensive assessment of its spillover effects on the economy. Moreover, these economic externalities provide invaluable insights for the formulation of policies and regulations concerning HSR. For instance, understanding how HSR influences land use and property values can guide decisions related to zoning and urban development policies. Therefore, grasping the exogenous factors that influence HSR is of paramount importance for policymakers endeavoring to devise a more pragmatic strategy for HSR development [8–10].

Investigating the spillover effects of various modes of transportation has been widely studied by the scholars, and an excellent study system has been established. Econometric model plays an irreplaceable role in such studies [11–14]. Currently, the primary models used for analyzing the spillover effects of rail transit are the panel data model [2, 15], spatial econometric model [6, 16–20], and DID model [21–24]. Table 1 lists some of the research on economic externalities associated with HSR and urban rail conducted using these three models. Panel data include

Table 1: Summary of relevant researches on the exogeneities of transportation.

Study method	Author(s)	Conclusion(s)	Innovation
Panel data model	Dai et al. [14]	Rail transit is able to enhance the housing prices of the surrounding houses	Combining hedonic model and panel data model
	Tian et al. [2]	The improvement in network position of HSR inhibits service industry agglomeration in peripheral regions	Constructing framework of complex network analysis and panel regression methods
DID model	Aslund et al. [1]	Commuter train access has little impacts on the employment development	Using the introduction of a local commuter train in Sweden
	Tian et al. [25]	HSR and service-sector agglomeration have positive correlation	Applying hypothetical counterfactuals to eliminate the exogeneity problem of dependent variables
	Li et al. [26]	The opening of HSR has a significant threshold effect on improving the efficiency of the service industry	Heterogeneity analysis of the impact of HSR on the service industry
	Zhu et al. [27]	The opening of HSR has a positive impact on urban land expansion	Analyzing the time lag impact of HSR
	Tang et al. [28]	HSR significantly promotes regional innovation	Investigating the impacts of urban form on the correlation between HSR and regional innovation
Spatial econometric model	Zheng et al. [6]	Urban rail transit can significantly improve urban air quality	Using several methods to test the robustness of the regression results
	Huang and Xu [29]	The construction of HSR narrows the regional differences in daily accessibility, but it will expand the differences in potential accessibility and location accessibility	Divide accessibility into location accessibility, potential accessibility, and daily accessibility

observational data for the same group of subjects at different time points and/or different locations, encompassing both spatial and temporal dimensions. Thus, the panel data model aids in identifying the effects of time trends, observed individual differences, and endogeneity, thereby providing a more comprehensive understanding and quantification of the impact of projects such as the economic externalities of HSR [30, 31]. Failure to capture the impact of policies at a certain time node is a drawback of the panel data model [15, 32]. Spatial econometric models focus on the interrelationships of influencing factors within geographic space [6, 35]. While the DID model allows for causal inference, i.e., it enables the determination of the impact of the opening and operation of HSR on urban economies by examining the changes in various economic indicators in cities before and after the HSR is introduced. The DID model is employed in this paper. Our research introduces two noteworthy modeling innovations. First, we utilize multiple robustness testing methods to enhance the credibility of the causal relationships derived from the DID model. These methods strengthen the basis for drawing meaningful conclusions. Second, within the factors affecting the DID model, we introduce a virtual HSR operation time to control for unobservable factors that might otherwise affect the urban economy. These refinements contribute to a more robust analysis of the spillover effects of HSR on urban economies.

However, due to the different stages of HSR development and variations in urban economic foundations, the impact of HSR on economy varies across cities [34]. Many studies indicate that the economic effects of transportation infrastructure are positive for highly developed cities, as the accessibility and connectivity of HSR can promote economic growth in these cities. However, for some smaller cities, the agglomeration and suction effects of HSR may lead to talent outflow [15]. Previous studies on heterogeneity have primarily focused on a geographical perspective [27, 35], while our paper will approach the economic development heterogeneity brought about by HSR from the standpoint of a city's development level, providing insights for maximizing the positive externalities of HSR. Specifically, we will explore the regional heterogeneity of HSR from two aspects: the impact of HSR operation on cities at different economic levels and which economic level of cities is more sensitive to HSR operation.

Most studies investigating the spillover effects of HSR or other modes of transportation on urban economy are usually empirical, meaning that although the positive externalities of HSR have been identified, the underlying mechanism of these externalities has not been fully understood yet [36, 37]. In addressing this issue, we have incorporated the flow of population, urban industrial structure, and scientific research level as intermediate variables in the models. These intermediate variables are introduced to shed light on the underlying mechanisms of the spillover effects of HSR on urban economies. Urban population serves as a critical indicator of the scale and dynamism of a city, which could influence how HSR impacts labor markets, demand for goods and services, and overall economic growth. City industrial structure reflects the composition of economic activities within a city, and variations in this structure may mediate the effects of HSR by determining which industries benefit the most from improved connectivity. Scientific research level represents the knowledge and innovation capacities of a city, which may be affected by enhanced accessibility through HSR and, in turn, influence the city's economic development. By introducing these intermediate variables, this study aims to delve deeper into the intricate mechanisms that drive the spillover effects of HSR on urban economies. It is anticipated that the analysis of these mediating variables will contribute to a more comprehensive understanding of the multifaceted dynamics in the relationship between HSR and urban economic development.

In summary, this work has three main innovations. First, we develop three robustness methods to verify the causal relationship derived from DID model. Second, the heterogeneity analysis is conducted to explore the impact of HSR operation on cities at different economic levels and which economic level of cities is more sensitive to HSR operation. Finally, unlike other empirical studies, intermediate variables are introduced to shed light on the underlying mechanisms of the spillover effects of high-speed rail (HSR) on urban economies.

To conduct a comprehensive analysis mentioned previously, this study puts forward three hypotheses of the relationship between HSR and urban gross domestic product (GDP), as shown in Figure 1, and verifies these hypotheses by statistical data analysis and modeling. These hypotheses, elucidating the impact of HSR on urban GDP and its underlying mechanisms, are progressively layered.

Hypothesis 1. The operation of HSR can directly contribute to the growth of urban GDP.

On the one hand, the introduction of HSR in a city facilitates more convenient intercity travel for residents, significantly amplifying the quantity and scale of economic activities. Thus, the overall economic situation will be improved. However, due to the siphoning effect of HSR, talent and markets may relocate to other areas with more developed economies. Similar to the exogeneities of HSR on urban air quality [38, 39], the spillover effects of HSR on GDP may exist heterogeneity for cities with different development levels. Therefore, it is necessary to investigate whether the effects of HSR on cities at different developmental stages differ.

Hypothesis 2. The urban GDP promoted by HSR exists heterogeneities among different cities.

On the other hand, cities may exhibit varied responses to the construction and expansion of HSR. For cities with more developed economic level, HSR may have a greater effect.

Hypothesis 3. The operation of HSR can promote the development of urban GDP by affecting several intermediate variables.

Furthermore, the operation of HSR may have indirect effects on urban GDP. As shown in Figure 1, HSR can accelerate the flow of population to the city where the

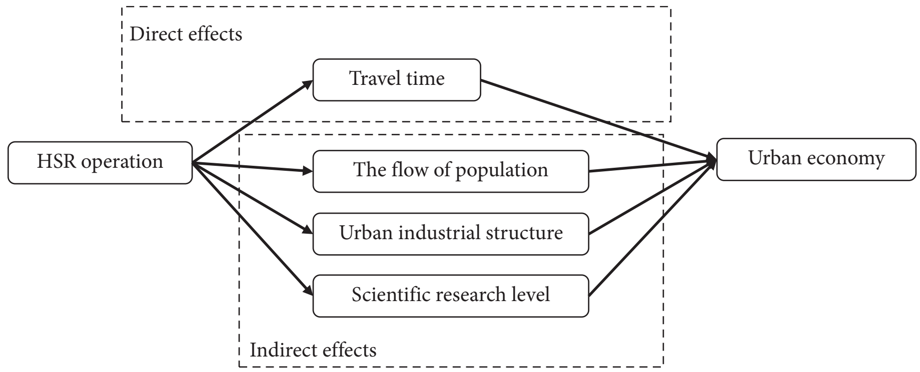

FIGURE 1: The mechanism of the effects of HSR on urban GDP.

high-speed rail operates, promote the upgrading of urban industrial structure, improve the level of urban scientific research, and thus promote the development of urban GDP. The indirect effects are often ignored in several relevant studies; hence, the positive effects of HSR have been underestimated.

The remainder of this paper is organized as follows. The statistical data are collected and preliminary analyzed in Section 2. Section 3 introduces common DID model and establishes two-stage DID model to study the direct and indirect effects of HSR on urban GDP. Section 4 presents the regression results of the models, and the robustness of the results is tested. The heterogeneities of HSR on cities with different development level are further analyzed. The conclusions are presented, and relevant policy suggestions are put forward in Section 5.

2. Data Description

To mitigate the impact of regional heterogeneity on the estimation results, thirty cities on the mainland of China which operated HSR by the end of 2019 are selected as study sites. Figure 2 depicts the spatial distributions of these cities. The selection of studied cities is based on two criteria: First, their distribution aligns with that of the HSR network, with a concentration of cities in the eastern region. Second, we prioritize provincial capitals and municipalities in the selection process. However, certain provincial capitals like Hohhot were excluded due to insufficient data. Given the rapid development of HSR in mainland China over the past decades, our research spans from 2010 to 2019 to capture this transformative period.

The economic variables reflecting the development level of the city are the explained variables of interests in this study. In order to measure the economic level of the city, we select real gross domestic product (GDP) instead of nominal GDP. Compared with nominal GDP, real GDP can more accurately reflect the quantity of goods that citizens can buy with their income, making it a more accurate indicator of the urban GDP's level. Real GDP agglomerates spatially, which could reflect the extent of economic agglomeration in a city, as illustrated by equation (1) and Table 1.

$$\mathrm{GDPag}_{\mathrm{it}} = \frac{\mathrm{GDP}_{\mathrm{it}}}{A_{\mathrm{it}}}, \quad (1)$$

where A_{it} denotes the area of city i in year t.

HSR variables are the main independent variable in this study. According to Chang et al. [4], we use 0-1 dummy variables (i.e., $\mathrm{HSR}_{\mathrm{it}}$) to describe whether city i introduces HSR in year t. Furthermore, a number of cities connected by HSR for city i in year t (i.e., $\mathrm{HSR\_line}_{\mathrm{it}}$) are introduced to measure the service level of HSR in the city more accurately, as shown in Table 2.

In order to examine the indirect effects of HSR on urban GDP, three mediating variables are taken into account in this study. We select resident population instead of registered population to measure the flow of population. Compared with resident population, registered population is more sensitive to policy, resulting in estimation bias. When a city is sufficiently attractive, its resident population will immediately increase significantly. Nevertheless, the change of registered residence population has a certain lag. Consequently, studying the effect of HSR on the urban GDP via resident population is a more accurate method. We use Ind calculated through equation (2) to measure the industrial structure of city i in year t.

$$\mathrm{Ind}_{\mathrm{it}} = \frac{\mathrm{RT}_{\mathrm{it}}}{\mathrm{RS}_{\mathrm{it}}}, \quad (2)$$

where RS denotes the proportion of added value of secondary industry in GDP. RT represents the proportion of added value of tertiary industry in GDP. The greater the value of Ind, the more industrial structure is transferred to the tertiary industry. STE is introduced to reflect urban scientific research level. Generally speaking, the more the government invests in the science and technology industry, the more developed the science and technology industry.

Moreover, several control variables are chosen to avoid estimate bias, as indicated in Table 1. Due to the lack of data, some data are filled through expectation maximization (EM) algorithm. To mitigate the potential impact of multicollinearity on the estimation results, variables that exhibit strong correlations are excluded from the analysis. Figure 3 presents the Pearson coefficients for all variables evaluated on the basis of equation (3). The darker color block indicates

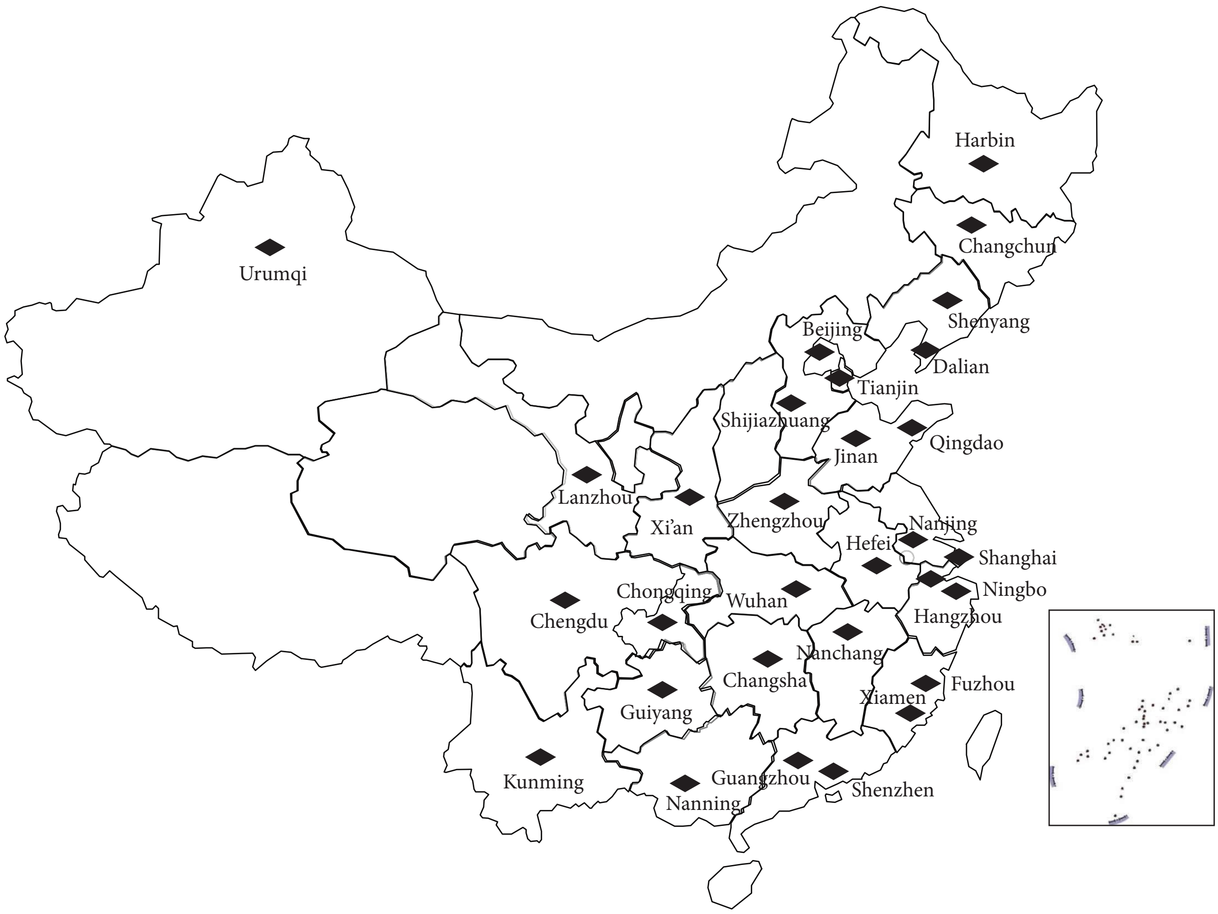

Figure 2: Distribution of the studied cities.

Table 2: Studied variables.

	Variables	Explanation	Units
Explained variables	GDP	Gross domestic product	Billion yuan
	GDPag	GDP agglomeration level	%
Explanatory variables of interest	HSR	0-1 Dummy variable	—
	HSR_line	Number of cities connected by HSR	Individual
Mediating variables	Pop	Population	Thousand individuals
	RP		
	RS	Proportion of added value of each industry in GDP	%
	RT		
	STE	Expenditure on science and technology	Million yuan
Control variables	First		
	Second	City level	—
	Third		
	PP		
	PS	Proportion of employees in each industry	%
	PT		
	EMP	Employment rate	%
	EE	Education expenditure	Million yuan
	T	The number of teachers	People
	S	Number of higher education institutions	Individual
	*P*vol	Passenger volume by all modes of transportation	Million people
	*C*vol	Cargo volume by all modes of transportation	Million ton

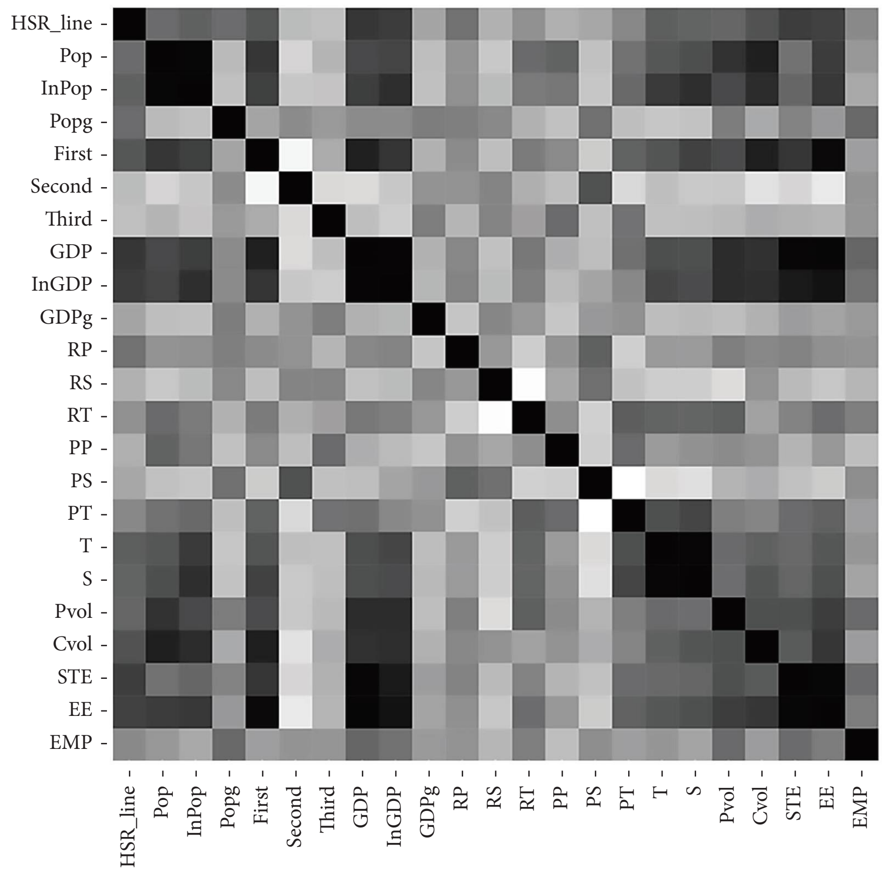

Figure 3: Pearson coefficients of the studied variables.

a higher linear correlation. The elements on the diagonal are all black, because the collinearity of the variable and itself is one. Figure 3 displays a strong relationship among HSR, GDP, and the mediating variables. However, the causal relationships need to be further studied by establishing DID models after removing interference caused by other factors.

$$\text{Pearson}_{X,Y} = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}}, \tag{3}$$

where X and Y denote two variables that are selected to calculate their correlation.

3. Modeling Study

Taking Zhang [24] as a reference, we initially establish a multiphase DID model to explore the economic impact of HSR, as follows:

$$\ln \text{GDP}_{\text{it}} = \alpha_1 \text{HSR}_{\text{it}} + X_{\text{it}}^T \beta + \mu_i + \lambda_t + \varepsilon_{\text{it}}, \tag{4}$$

where GDP_{it} denotes the economic development level of city i in year t. X_{it} is a vector composed of control variables illustrated in Section 2. According to Tao et al. [20], when determining the spillover effects of transportation modes in city level in China, μ_i ought to be regarded as fixed effect instead of random effect. Therefore, μ_i represents individual fixed effect that differs across cities, and λ_t denotes time fixed effect which measures the change of years in this research. ε_{it} presents random interference term. α_1 measures the causal elastic relationship between HSR_{it} and GDP_{it}. However, due to the endogenous problems of independent variables and confounding dynamics, the robustness of estimate results regressed by equation (4) needs to be tested. This study employs three methods to verify the robustness of the model.

If strong spatial correlations exist among the studied cities, spatial econometric models are better appropriate for the data than DID models. Consequently, the first method is to calculate the Moran's I index and Geary's C index of each variable, as given in equations (5) and (6), in order to measure the spatial autocorrelation degree of studied variables. The value of Moran's I is between −1.000 and 1.000. When Moran's $I > 0.000$, a positive spatial association exists between the studied variables. The larger the absolute value of Moran's I, the more obvious the spatial correlation of the variables. Geary's C typically ranges between 0.000 and 2.000, with Geary's $C < 1$ indicating a spatial positive correlation for the variable.

$$\text{Moran's}\, I = \frac{\sum_{i=1}^{n}\sum_{i=1}^{n} w_{\text{ij}}\left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right)}{S^2 \sum_{i=1}^{n}\sum_{i=1}^{n} w_{\text{ij}}}, \tag{5}$$

$$\text{Geary's}\, C = \frac{(n-1)\sum_{i=1}^{n}\sum_{i=1}^{n} w_{\text{ij}}\left(x_i - x_j\right)^2}{2\left(\sum_{i=1}^{n}\sum_{i=1}^{n} w_{\text{ij}}\right)\left[\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2\right]}. \tag{6}$$

The second method is changing the explained variable to GDP_{it}. If the quantitative relationship and the elastic relationship are both positive and significant, the causal relationship is verified. The third method is setting virtual HSR open years. The regression results of equation (1) cannot be accepted even though they are significant if GDP_{it} is improved by other invisible factors affecting GDP_{it} at the same time of HSR. The main idea of the third method is to set virtual HSR open years to avoid such a situation, as shown in equation (7). If α_2 is insignificant, the causal relationship between HSR and urban GDP is verified, indicating that HSR, instead of other invisible factors, affects urban GDP. While if α_2 remains positive and significant, it is other influencing factors instead of HSR that promote the development of urban GDP.

$$\ln \mathrm{GDP}_{it} = \alpha_2 \mathrm{HSR}_{\mathrm{virtual\_it}} + X_{it}^T \beta + \mu_i + \lambda_t + \varepsilon_{it}. \quad (7)$$

Equations (8) and (9) show the two-stage DID model that can be regressed using 2SLS method. M_{it} is the mediating variables introduced in Section 2. Equation (8) represents the first-stage regression that measures the effects of HSR on mediating variables. Equation (9) is the second-stage regression investigating the impacts of mediating variables to urban GDP. In case α_3 and α_4 are all positive and significant, HSR affects mediating variables and then improves urban GDP. The indirect effects of HSR can be found and proved in this way.

$$M_{it} = \alpha_3 \mathrm{HSR}_{it} + X_{it}^T \beta + \mu_i + \lambda_t + \varepsilon_{it}, \quad (8)$$

$$\ln \mathrm{GDP}_{it} = \alpha_4 M_{it} + X_{it}^T \beta + \mu_i + \lambda_t + \varepsilon_{it}. \quad (9)$$

4. Regression Results

In this section, the DID models are first applied to investigate the spillover effects of HSR on urban GDP and its agglomeration. Thereafter, the three methods mentioned above are employed to test the robustness of the regression results. Then, the heterogeneities of HSR on cities with different development levels are further analyzed. Finally, the indirect impacts illustrated in Figure 1 and the mechanism of HSR promoting urban economic development are identified.

4.1. General Results. Tables 3 and 4 present the estimate results of equation (6). Table 3 shows the effects of HSR on urban GDP. The values in brackets are the p value of each coefficient. The values in brackets in the subsequent tables have the same meaning. The main explanatory variable is HSR in columns 1, 3, and 5, and it changes to HSR_line in columns 2, 4, and 6. Column s1 and 2 do not introduce control variables. Columns 3 and 4 add control variables into the model, and columns 5 and 6 add individual fixed effects and time fixed effects. The coefficients of HSR and HSR_line are all positive and significant, indicating that the operation and expansion of HSR can effectively promote the development of urban GDP. After adding the fixed effects and the control variables into the model, the R square significantly improves, indicating that it is essential to take them into consideration. The values of HSR and HSR_line decrease after adding control variables, implying that if the effects of other factors and the influences of individual and time are ignored, the effects of HSR on urban GDP will be overestimated. In Table 3, all the fixed effects and the control variables are put into the regression progress. In columns 5 and 6, the coefficients of HSR and HSR_line are all positive and significant at 0.01 level, which demonstrates that the construction of HSR is able to promote urban GDP remarkably. HSR can increase the GDP of a city by 14.200%, and for each additional HSR line, the urban GDP will increase by 7.200%. The opening and operation of HSR makes the intercity travel more convenient for citizens, hence increasing economic activities between cities and promoting economic growth.

The exogeneity of HSR on urban economic agglomeration is presented in Table 4. Each column in Table 4 has the same meaning as shown in Table 3, except for the explained variable ln GDPag. Columns 5 and 6 clarify that the operation of HSR can significantly promote the economic agglomeration of a city. The opening of HSR can increase the economic agglomeration level of the city by 14.200%. The economic agglomeration level of the city will increase 7.200% on average when a new HSR line is constructed in the city. In the past decade, the majority of Chinese cities have developed at a high speed.

The land area of the city has expanded rapidly. Despite this, HSR still contributes positively to the development of GDP, even when urbanization is considered. HSR can significantly and comprehensively promote the development of urban GDP.

From Tables 3 and 4, it can be concluded that HSR may efficiently and considerably enhance both the city's economic development and its agglomeration. Section 1's Hypothesis 1 is proven. However, as demonstrated in Section 3, the results cannot be accepted if they are not robust, even if the coefficients are significant and positive. Therefore, it is necessary to assess the robustness of the estimate findings regressed by DID models to confirm their availability.

4.2. Robustness Tests. Three methods are applied to verify the robustness of estimate results obtained in Section 4.1. Table 5 presents the results of spatial correlation analysis of each variable of interest. All variables' Moran's I index is close to 0.000 and Geary's C index is close to 1.000. Furthermore, the coefficient of each index is not statistically significant at 0.01 level, which indicates that the spatial correlations of the studied variables are insignificant. It is appropriate to employ DID model for regression.

The regression results of the second and third methods are presented in Table 6. Columns 1 and 2 replace the explained variable with GDP, while columns 3 and 4 replace the explained variable with GDPag. The coefficients of HSR and HSR_line remain positive and significant at 0.01 level, confirming the robustness of the results regressed in Section 4.1. Column 5 in Table 5 has the same meaning as column 5

Table 3: The causal elastic relationship between HSR and urban GDP.

Dependent variables	ln GDP					
	(1)	(2)	(3)	(4)	(5)	(6)
HSR	0.496 (0.000)		0.137 (0.000)		0.142 (0.000)	
HSR_line		0.126 (0.000)		0.069 (0.000)		0.072 (0.000)
Control variables	No	No	Yes	Yes	Yes	Yes
μ_i and λ_t	No	No	No	No	Yes	Yes
Constant	1.522 (0.000)	1.580 (0.000)	0.719 (0.029)	0.595 (0.039)	1.206 (0.026)	0.868 (0.033)
R^2 overall	0.124	0.329	0.882	0.869	0.852	0.838
R^2 within	0.294	0.670	0.779	0.873	0.782	0.875
R^2 between	0.102	0.326	0.901	0.869	0.869	0.843
City	30	30	30	30	30	30
Year	10	10	10	10	10	10
Observations	300	300	300	300	300	300

Table 4: The causal elastic relationship between HSR and urban economic agglomeration.

Dependent variables	ln GDPag					
	(1)	(2)	(3)	(4)	(5)	(6)
HSR	0.496 (0.000)		0.152 (0.000)		0.142 (0.000)	
HSR_line		0.126 (0.000)		0.071 (0.000)		0.072 (0.000)
Control variables	No	No	Yes	Yes	Yes	Yes
μ_i and λ_t	No	No	No	No	Yes	Yes
Constant	−3.141 (0.000)	−3.082 (0.000)	−3.653 (0.000)	−4.084 (0.000)	−3.456 (0.000)	−3.793 (0.000)
R^2 overall	0.099	0.244	0.676	0.645	0.579	0.544
R^2 within	0.294	0.668	0.778	0.873	0.782	0.875
R^2 between	0.114	0.312	0.670	0.630	0.577	0.541
City	30	30	30	30	30	30
Year	10	10	10	10	10	10
Observations	300	300	300	300	300	300

Table 5: The results of the first method.

Variables	Moran's I	p value	Geary's C	p value
GDP	−0.022	0.462	1.027	0.328
ln GDP	0.003	0.215	0.956	0.170
Pop	0.014	0.088	0.905	0.159
ln Pop	0.035	0.047	0.898	0.030
RS	−0.047	0.276	1.023	0.343
RT	−0.070	0.106	1.055	0.177
STE	−0.026	0.496	1.052	0.247

in Table 2. Column 6 changes HSR to $HSR_{virtual}$. From the comparison of column 5 and column 6, it can be found that the coefficient of HSR turns insignificant when replacing HSR with $HSR_{virtual}$, indicating that HSR, not other influencing factors, promotes the growth of the urban GDP.

In this section, three methods are used to confirm the robustness of the regression results, and it can be concluded that HSR has injected vitality into the urban GDP and agglomeration. However, different cities may benefit differently from the opening of HSR [40]. Therefore, the heterogeneities of HSR on cities with different development levels ought to be investigated.

4.3. Heterogeneity Analysis. City level is a measurement standard indicating the complete development level of a city on the Chinese mainland. Hence, this study selects city level to divide the studied cities. Table 7 presents the heterogeneity analysis of HSR. Columns 1 and 2 show the economic effects of HSR on first-tier cities, columns 3 and 4 denote the economic effects of HSR on second-tier cities, and the economic effects of HSR on third-tier cities are shown in columns 5 and 6.

Different from Hypothesis 2 presented in Section 1, although heterogeneities exist in the ability of HSR promoting urban GDP among different cities, these abilities are largest in the third-tier cities, followed by the first-tier cities and the second-tier cities. This phenomenon is strongly related to the indirect effects of HSR on urban GDP. Compared with the first-tier cities and the second-tier cities, the populations of the third-tier cities are relatively fewer, and the urban infrastructure is better developed and suitable for every citizen. In addition, the industrial structure of the

Table 6: The regression results of the second and third methods.

Dependent variables	GDP		GDPag		ln GDP	
	(1)	(2)	(3)	(4)	(5)	(6)
HSR	320.954 (0.000)		0.041 (0.000)		0.142 (0.000)	
HSR_line		110.876 (0.000)		0.016 (0.000)		
$HSR_{virtual}$						0.009 (0.649)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
μ_i and λ_t	Yes	Yes	Yes	Yes	Yes	Yes
Constant	615.902 (0.000)	−967.040 (0.098)		−0.761 (0.000)		1.060 (0.059)
R^2 overall	0.074	0.513	0.035	0.003	0.852	0.000
R^2 within	0.116	0.753	0.043	0.482	0.782	0.362
R^2 between	0.079	0.456	0.051	0.018	0.869	0.003
City	30	30	30	30	30	30
Year	10	10	10	10	10	10
Observations	300	300	300	300	300	300

Table 7: Heterogeneity analysis between HSR and urban GDP.

Dependent variable	ln GDP					
	(1)	(2)	(3)	(4)	(5)	(6)
HSR	0.225 (0.068)		0.156 (0.000)		0.933 (0.009)	
HSR_line		0.080 (0.000)		0.075 (0.000)		0.134 (0.003)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
μ_i and λ_t	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.430 (0.789)	0.645 (0.829)	0.999 (0.062)	0.655 (0.110)	17.972 (0.039)	3.714 (0.320)
R^2 overall	0.487	0.539	0.762	0.686	0.022	0.259
R^2 within	0.786	0.929	0.789	0.876	0.975	0.982
R^2 between	0.619	0.204	0.763	0.628	1.000	1.000
City	5	5	23	23	2	2
Year	10	10	10	10	10	10
Observations	50	50	230	230	20	20

third-tier cities has more room for development. As a consequence, when HSR opens in the third-tier city, it will improve the economic development of city in a more efficient way. However, this does not mean that priority should be given to the development of HSR systems in the third-tier cities, as the construction of HSR network should not be divorced from the basic principle of passenger demand.

From heterogeneity analysis, we derived several interest conclusions and had some new problems. To explore the full potential of HSR, it is vital to investigate the fundamental mechanisms of HSR's contribution to the urban GDP.

4.4. Indirect Impacts. Equations (7) and (8) provide an efficient method for determining how HSR influences the urban GDP. The indirect effects of high-speed rail on metropolitan economies are shown in Table 8. In columns 1, 2, and 3, urban population serves as the mediating variable. In columns 4, 5, and 6, the industrial structure is introduced as the mediating variable. In columns 7, 8, and 9, expenditure on science and technology is used to examine indirect effects.

The regression results presented in Table 8 demonstrate that HSR has the potential to facilitate population migration, expedite the transformation of urban industrial structure, and enhance investments in science and technology within cities. First, urbanization is closely associated with increased economic activity, and as economic activity expands, it inevitably contributes to the growth of the urban GDP. Second, the transformation of the industrial structure leads to a higher proportion of the tertiary industry. The expansion of the tertiary industry, particularly the service sector, not only generates significant economic activity but also stimulates growth in other industries. Third, innovation serves as a driving force for urban economic development. The city's investment in science and technology plays a crucial role in enhancing its economic vitality. HSR indirectly supports the growth of the urban GDP through these three factors. Therefore, Hypothesis 3 has been confirmed.

In order to maximize the positive impact of high-speed rail on urban economic development, cities must make adequate preparations for the following aspects before opening or expanding high-speed rail: (1) ensure that urban infrastructure is sufficient to accommodate expected population growth, (2) prepare for industrial restructuring, and (3) the government should provide sufficient funds for technological innovation. These measures will enable high-speed rail to play a more comprehensive role in the economic development of cities. The introduction of HSR systems may have negative consequences on cities with inadequate infrastructure. This is due to the siphon effect,

Table 8: Indirect impacts analysis.

Dependent variable	ln Pop (1)	ln Pop (2)	ln GDP (3)	ln GDP (4)	Ind (5)	ln GDP (6)	STE (7)	STE (8)	ln GDP (9)
HSR	0.053 (0.000)				0.260 (0.002)		2181.742 (0.003)		
HSR_line		0.018 (0.000)		0.070 (0.000)				1061.920 (0.000)	
Mediating variables			0.916 (0.000)			0.717 (0.000)			0.003 (0.000)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
μ_i and λ_t	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.580 (0.000)	1.257 (0.000)	−4.299 (0.000)	1.065 (0.000)	1.045 (0.000)	1.108 (0.000)	3557.410 (0.000)	2446.625 (0.047)	1.718 (0.000)
R^2 overall	0.329	0.063	0.761	0.053	0.014	0.120	0.040	0.209	0.486
R^2 within	0.670	0.259	0.797	0.086	0.035	0.377	0.029	0.248	0.219
R^2 between	0.326	0.117	0.767	0.034	0.003	0.089	0.065	0.270	0.564
City	30	30	30	30	30	30	30	30	30
Year	10	10	10	10	10	10	10	10	10
Observations	300	300	300	300	300	300	300	300	300

where more people migrate from these cities to other locations, resulting in a redistribution of production resources. This outcome serves as a warning to policymakers. Therefore, when expanding a country's HSR network, it is crucial to consider the development level of each city rather than blindly connecting every city on the map. A well-thought-out HSR development plan should aim to maximize the positive externalities of HSR while minimizing its negative effects to the greatest extent possible.

5. Conclusions

This study develops DID models to assess the effects of HSR operation on the urban GDP. The panel data consist of thirty cities operating HSR by the end of 2019, covering the period from 2010 to 2019. Panel data model is applied to investigate the causal elastic relationship between HSR and urban GDP and agglomeration, respectively. The regression results are evaluated using three methods. In addition, the ability of HSR promoting urban GDP exists heterogeneities among cities with different development levels. Also, mediating variables play an important part in the effects of HSR on urban GDP. The innovation of this study can be summarized into the following three aspects.

(1) *HSR Economic Externality Clarification.* We emphasize the significance of understanding the economic externality of HSR in assessing its impact on the economy and its role in informing policy decisions

(2) *Comprehensive Econometric Modeling.* Our study employs robust econometric models, including panel data and spatial autoregressive models, aiming to mitigate bias and enhance the accuracy of estimations

(3) *Mechanistic Insights into HSR Effects.* We propose and test three progressive hypotheses regarding the relationship between HSR and urban GDP, contributing to a deeper understanding of the mechanisms through which HSR influences urban economies

Indeed, HSR can have significant impacts on urban GDP and agglomeration. First, HSR can contribute to the growth of urban GDP. The strongest impact is observed in third-tier cities, followed by first-tier and second-tier cities. This pattern suggests that HSR can bring more opportunities for economic activities, such as increased business interactions, trade, tourism, and investment, to these cities. As a result, the urban economies in these areas can experience considerable growth. Second, HSR facilitates the migration of people to urban areas. Improved connectivity and reduced travel time provided by HSR make urban areas more attractive for both individuals and businesses. This influx of people can stimulate urban development and modernization. Additionally, HSR can encourage the upgrading of urban industrial structures by attracting new industries, promoting innovation, and fostering economic diversification. Finally, the presence of HSR contributes to enhancing the quality of urban scientific research. By connecting cities and improving accessibility, HSR enables researchers and academics to collaborate more easily across different urban areas. This collaboration facilitates the exchange of knowledge, expertise, and resources, thereby improving scientific research and innovation in urban centers.

To optimize the function of HSR and maximize its societal benefits, policymakers should consider the following measures. Investing in urban science and technology is crucial to harness the potential of HSR. This includes supporting research institutions, promoting innovation hubs, and fostering a culture of scientific inquiry. By focusing on science and technology, cities can attract talent, foster entrepreneurship, and drive economic growth. In addition, policymakers should encourage the upgrading of urban industrial structures. This involves attracting industries with high value addition, promoting sustainable practices, and supporting the development of knowledge-intensive sectors. By diversifying and modernizing their industrial base, cities can improve productivity, create employment opportunities, and enhance their competitiveness. Finally, given the population upsurge resulting from HSR, investments in urban infrastructure are imperative to meet the escalating needs of residents and businesses. This includes expanding transportation networks, developing residential areas, improving public services, and ensuring access to amenities. Adequate infrastructure development ensures that urban areas can accommodate the increased demand and provide a high quality of life for their residents. In summary, HSR can indeed promote urban GDP and agglomeration. By focusing on urban science and technology development, upgrading industrial structures, and constructing necessary infrastructure, policymakers can optimize the benefits of HSR and support sustainable urban development. However, it is important to note that, due to the lack of data, the direct effects of HSR are not investigated in this research, which needs to be studied in the future work.

Data Availability

The data are collected from the corresponding urban transportation bureaus in China.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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