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Does High-Speed Railway Promote the Quality of Urbanization? From a Dynamic Network Perspective

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Abstract: Applying the improved social network analysis method and the idea of rolling window regression, this paper explores the impact of HSR network on the quality of urbanization and its dynamics. Based on a sample of 273 cities in China over 2009–2019, we find that the high-speed railway network has an increasing positive effect on the quality of urbanization, which proves the existence of network effect. The empirical results further show that this effect is closely related to the coverage rate of high-speed rail network. In addition, heterogeneity analysis reveals that urban agglomeration cities are the main beneficiaries. Academically, our study provides a plausible explanation and evidence from network size differences for the two conflicting views of the HSR effect. Practically, we also propose some important policy implications for countries in different high-speed rail network construction stages.

Keywords: high-speed railway; quality of urbanization; dynamic network; improved social network analysis; spatial econometric model

1. Introduction

According to World Bank statistics, by the end of 2019, the world urbanization rate has exceeded 55%, marking that the human has entered the "urban era". In this context, transportation infrastructure construction and urbanization quality (a sustainable development), have become a new research focus in the field of transportation economics. Theoretically, the improvement of transportation condition is beneficial to enhance the efficiency of economic activities. From the theory of transaction costs, the decline in transport costs will facilitate the formation of more transactions that were originally subject to spatial constraints, which in turn allows factor resources to be delivered to a more potential user [1]. Therefore, in order to achieve an efficient and sustainable development, a more convenient means of transport comes into being. As an inter-regional fast transportation tool, the most direct role of high-speed railway is to reduce the loss of time value in travel. Since it is mainly designed for passenger service, early studies focused on whether HSR could achieve population diversion from high-density areas and thus promote regional equilibrium and economic growth [2]. The construction of the Shinkansen in Japan and the Beijing-Shanghai line in China are two typical examples. But with the opening of high-speed railway in more non-developed countries and regions, its role is no longer limited to alleviating population pressure. Instead, its strong positive externality (e.g., spatio-temporal compression, zone upgrading, green and low-carbon) has become the basis for the high cost of construction and attracted widespread research interest.

A series of studies have highlighted the impact of HSR on the quality of urbanization from three aspects: factor inputs, factor appreciation, and factor mobility. Specifically, the construction and development of high-speed railway paly a positive role on increasing employment position[3], raising land value [4] and promoting talent exchange [5]. Most of these studies make extensive use of presence, accessibility and service indicators to characterize local HSR and provide detailed individual heterogeneity analysis in terms of city size[6], geographic location [7], and economic level [8]. In contrast, few other studies have extended their horizons to the HSR 's location effect and agglomeration effect, citing metrics such as degree centrality, betweenness centrality, and closeness

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centrality to analyze the impact of changes in the importance of node cities from a static network perspective[9–11].However, restricted by the HSR construction process and the geographical conditions of various countries, an analysis from the perspective of dynamic network has not been carried out. In the dynamic network perspective, in addition to the two factors of the presence of nodes and the strength of connections, the size of the HSR network itself is also treated as an endogenous variable [12], which is overlooked in the static network perspective. The famous Metcalfe's law further states that the value of the network is proportional to the square of the number of nodes in the network, which is a marginal increasing nonlinear relationship. This heterogeneity analysis from network scale variation will be the biggest difference between this article and others.

HSR infrastructure is well suited for network analysis due to its tangible stations and tracks (as opposed to roads and civil aviation), which correspond to the nodes and links in the network, respectively. With a higher coverage in HSR countries, a spatial network structure has become increasingly prominent. Taking China as an example, by the end of 2019, China 's high-speed railway mileage has exceeded 35,000 kilometers, and more than 200 cities and 100 lines have been connected to the HSR network. Nearly 70% coverage also basically set up China's eight vertical and eight horizontal HSR network structure. As a consequence, under the condition of network, network effect (network externality) may become the third force besides “growth pole effect” and “corridor effect”. This means that with the increase of HSR cities and lines, all cities may obtain greater benefits from the expansion of network scale. Taking use of this superb setting with the aid of a robust spatial empirical method and rolling window idea, this study examines how changes in the size of the HSR network affect the quality of urbanization.

In view of the distance advantage and scale advantage of China ' s HSR network, this paper still selects China as the analysis object which is the same as most studies. Firstly, using panel entropy weight method (PEWM), we measure the urbanization quality of 273 cities in China from 2009 to 2019 from population, economy, space, environment and society. Secondly, we draw on social network analysis to calculate the relative degree centrality and betweenness centrality of HSR cities to reflect the effects of adjacency and non-adjacency, respectively. To compare the differences between non-network and local network perspectives, HSR dummy variables and absolute centrality are also introduced. Thirdly, combining the idea of rolling window regression and spatial econometric tools, we construct a spatial Durbin model to test the effects of HSR network development on urbanization quality in different periods. Fourthly, since the urban agglomeration strategy is an important basis for the layout of HSR and the improvement of urbanization quality in China, we further verify the development differences between urban agglomeration cities and non-urban agglomeration cities.

Our study may contribute to the existing literature in the following three points: (1) From the perspective of research, we explore the relationship between HSR and urbanization quality from the perspective of dynamic and global network for the first time, which fills a gap in the heterogeneity analysis of time dimension. (2) In terms of research method, we innovatively make a combination between spatial econometric model and rolling window regression, which provides a feasible method for spatial-temporal two-dimensional analysis. (3) As for the research conclusion, we find a two-way nonlinear effect of “negative to positive” and “weak to strong” in the HSR network, which is different from the one-way linear effect of the existing HSR studies. In addition, this paper also conducts the heterogeneity analysis according to urban agglomeration classification instead of geographic location or population size, which can provide a new idea for the analysis of city heterogeneity.

The subsequent structure of the article is arranged as follows. The second part is the literature review. The third part is the research methodology, sample, and data. The fourth part is the empirical results. The fifth part is conclusions and implications

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2. Literature review

2.1. Measurement of the characteristics of HSR network

Existing studies have measured the characteristics of HSR networks in three main aspects, including HSR network context, HSR network benefit, and HSR network structure. Based on the established facts in the sample period, some scholars take the opening and operation of HSR under the network background as the characteristic variable of HSR network, such as HSR dummy variable [13–15], HSR cities numbers [16] and connectivity (measured by train frequency passing the territory) [17]. Although such indicators can reflect changes in the size of the HSR network to some extent, they are not meaningful for realistic network analysis. In contrast, it may be more appropriate for some scholars to measure the HSR network indirectly through the benefits generated by the HSR network. This benefit is widely summarized as the improvement of accessibility, including travel time [18,19][18][18], economic potential [11], number of passengers [19], geographical distance [20] and other proxy variables. Moreover, just few scholars adopt a direct measurement from a network perspective. They try to introduce social network analysis methods to portray the HSR characteristics of cities from the infrastructure and service of HSR network [11,21–25]. For example, Liu et al. [9] applies point degree and closeness centrality of the HSR infrastructure to measure the total accessibility and network structure. Taking into account the actual provision and use of HSR services, Liu et al. [10] also supplement the travel time and daily frequency into degree, betweenness and harmonic centrality indices by using China's HSR timetable data, which reflect both the quantity and quality of connections.

However, these studies are still limited to station areas or related cities, and do not consider the wider geographical scope [18]. With the rapid expansion of HSR network, the establishment of new nodes and connections does not necessarily enhance the importance of cities throughout the network. This is due to the fact that the existence of a competitive urban relationship can make the local HSR advantage further weaken or even turn into a disadvantage, especially when the growth rate of HSR connection in a city is less than the national average. Therefore, a relative centrality measurement method should be considered and adopted, which is currently lacking in the research.

2.2. HSR, production factors and urbanization quality

Compared with the traditional urbanization (only considers the proportion of urban population or land [26–28]), the quality of urbanization is a better state of factor allocation based on the economic setting of resource scarcity, which reflects the level of urban comprehensive and sustainable development. Although there is no unified measurement index or index system, efficiency, fairness and environmental protection are generally taken into account [29–31]. High-speed railway can directly accelerate the speed and frequency of population flow [15], and then drive the successive flow of labor [32], capital [33], knowledge [5] and other elements, which is of great significance to the improvement of urban development quality. Existing studies have explored extensively the relationship between HSR and high-quality urban development from the dimensions of population, economy, space, environment and society. (1) population dimension: mainly includes the number of tourists [34,35], commuting population [36] and population urbanization [28,37]. For instance, by dividing population movements into long-term, temporary, periodic and reciprocal mobility, Wang et al. [15] construct a DID model using the 2005-2016 panel data of the Yangtze River Delta region of China, and find that the opening of HSR has a negative impact on long-term population mobility and population urbanization, but a significantly positive effect on short-term population migration and the tertiary industry, especially tourism, which is conducive to promoting industrial upgrading and improving the quality of urbanization. (2) Economy dimension: direct investment multiplier effect and indirect space-time compression effect. One the one hand, as a major infrastructure construction project, HSR investment can produce broad industrial association effects, driving the increase of relevant industrial output, thus promoting regional economic growth through the enlargement of investment multiplier effect [38]. One the other hand, the improvement of transportation facilities can reduce the operating costs of enterprises [39] and expand the market scale, which is conducive to refining professional divisions and boosting economic growth [40]. In addition, networking of transportation infrastructure can link the economic activities of different regions into a whole, making the boundaries of cities and urban agglomerations constantly overflow, breaking the spatial limitation of knowledge spillover, which is conducive to the more innovations [28]. (3) Space, society and environment dimensions. Based on land-use remote sensing data from 1990 to 2015 of the Yangtze River Delta areas, Wang et al. [41] find that the opening of HSR played an active role in the expansion of urban space and other construction land, but accelerate the loss of agricultural land. This effect can be cumulative, indicating that the longer the HSR opening time, the faster the urban land use changes. Yu and Pan [42] construct a study based on the data of 287 prefecture-level cities in China from 2008 to 2016 and discover that HSR opening can narrow the income gap between urban and rural areas by improving the flow efficiency of high-skilled labor. What's more? Using data for Chinese cities from 2003-2014, the study of Jia et al. [43] further point out that the increased intensity of HSR services significantly reduces urban CO2 emissions, due to transportation substitution, market integration, industrial structure and technological innovation.

Reviewing the existing studies, scholars have achieved relatively fruitful results on HSR networks and urban development, including various aspects of urban system, heterogeneity analysis of a wide range of individual dimensions, and the introduction of a network perspective. However, there are still three points worthy of improvement. First, the research object focuses on a single dimension of urban development quality (e. g. population mobility or economic growth), lacking a comprehensive consideration. Second, the research perspective is limited to the site or its adjacent area, rather than a wider scope. Third, the research process is trapped into individual and spatial differences, ignoring temporal heterogeneity, that is, changes in the scale of the HSR network. A study of Kim and Sultana [44] strongly supports that the impact of urban accessibility is different for each South Korean HSR network expansion phase. To address the above questions, this paper constructs a system of urbanization quality indicators, using relative centrality indicators (which consider a wider range of linkages), and examines the impact of China's high-speed railway network on urbanization quality and heterogeneity analysis in a phased manner.

2.3. HSR network and quality of urbanization: hypothesis

According to transaction cost theory [1], a reduction in transaction costs can increase the opportunity of negotiation and cooperation between the parties, leading to a more reciprocal and effective contract (resource allocation decision). As an improved transportation mode, high-speed railway can reduce cross-regional transaction costs (mainly transportation or search costs), promote the formation of more transaction activities, and further improve the allocation efficiency of labor, land, capital, knowledge and other factors. On the one hand, due to the weakening of space constraints, some new business will emerge and become popular, such as intercity commuting, job-housing separation and TOD project, which will enable more idle or cheap resources to be used and appreciated. On the other hand, the frequency of some existing transactions will also increase as the loss of time value decreases, particularly activities that need to return in one day such as academic exchanges, business negotiations and short-distance travel, which enhances the mobility and utilization efficiency of factors. In addition, the increased accessibility of cities under networked conditions may lead to a more adequate exchange of factors. Based on this, we propose hypothesis 1: *In a long run, high-speed railway network can promote the quality of urbanization.*

In a further, the emphasis of dynamic network analysis is to explore whether there is a nonlinear network effect. According to the new economic geography theory [45], the short-term and long-term effects of HSR construction on peripheral areas are different. There is heterogeneity in the effects of transportation cost changes on "center-periphery" areas at different stages, that is, at the initial stage of HSR opening, the decrease of transportation costs between the central and peripheral cities is more beneficial to the increase of population and industrial agglomeration in the central area, but with the further improvement of transportation infrastructure, the decrease of transportation costs will be more beneficial to the peripheral areas. The network externality theory also suggests that as the number of nodes increases, the utility gained by individual nodes will grow exponentially.

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Empirically, Liu and Su [46] proved that the impact of transportation infrastructure on urbanization is inconsistent across subperiods. Therefore, we similarly propose Hypothesis 2: *The impact of the HSR network on the quality of urbanization is different at each stage* (It is worth noting that despite the relatively short duration of China's high-speed rail construction, the overall process is nearing completion).

Then, regarding the heterogeneity of individual dimensions, HSR has a significant advantage over civil aviation and roads for medium-distance travel. Chen and Haynes [19] and Adler et al. [47] find that high-speed railway is more competitive in the market on 500-800km routes. This distance interval may cater more to the demand of inter-city travel in urban agglomerations. Therefore, this paper proposes hypothesis 3: *High-speed rail network will be more beneficial to the development of urban agglomeration cities.*

3. Research methodology, sample, and data

3.1. Variable measures

3.1.1. Measurement: Relative degree centrality and betweenness centrality

First, in terms of network model setting, we employ the L-space model, that is, there is no multiple connections between two nodes. Second, since some cities may have opened more than one HSR station, we define a HSR city as a node in order to avoid double counting. Then, we use the improved degree and betweenness centrality formula [12] to measure the importance of cities in HSR network. This formula is a standardized result and has two advantages for this study :(1) the influence of network size change is eliminated in variable selection, which reduces the endogeneity problem of dynamic analysis; (2) nodes are placed in a broader network perspective, which highlights the interaction and comparative advantage between nodes. Specifically, degree centrality reflects the ability of direct link between a node itself and other adjacent nodes. It can be defined as Equation (1)

$$RDC_{ij} = \frac{1}{N-1} \cdot \sum_{j=1,i\neq j}^{n} K_{ij} \tag{1}$$

Where N refers to all cities with HSR that year, n = N-1, K_{ij} represents the HSR connection between city j and city i, If i and j are directly connected through a HSR line, K_{ij} = 1, otherwise, K_{ij} = 0.

Betweenness centrality refers to the number of shortest paths passing through a node. It assesses the capacity of a node's indirect control over other nodes and potentially the entire network, defined as Equation (2)

$$RBC_i = \frac{2}{N^2 - 3N + 2} \cdot \sum_{f\neq i\neq t}^{n} \frac{\alpha_{od}^{i}}{\delta_{od}} \tag{2}$$

Where α_{od}^{i} represents the number of HSR connections through city i among all the shortest HSR connections from city o to city d, δ_{od} represents all the shortest HSR connections from city o to city d.

3.1.2. Measurement: Quality of urbanization

Drawing on the research of Wang et al. [48], quality of urbanization is mainly divided into five aspects: population, economy, space, environment, and society. For population urbanization, quality of urbanization not only seeks to improve the urbanization rate, but also takes into account the urban population density and the non-primary industrial population which reflect the utilization efficiency of urban resources and the employment structure respectively. In terms of economy, per capita GDP and the proportion of output value of secondary and tertiary industries are two common indicators to measure the quality of economic development, reflecting individual contribution and structure composition of regional economic development respectively. Besides, GDP density of non-agricultural industries are supplemented to reflect the space utilization rate of economic growth. For the space, how to give full play to the value of land resources and improve land utilization is another key issue of urbanization quality. The capita road areas and capita living areas are two good indicators of urban congestion. The proportion of built-up area and per capita built-up area respectively reflect the construction scale and utilization efficiency of urban space. Regarding the environment, sustainable development clearly emphasizes "ecological civilization" and seeks a "green and environmentally friendly " development mode. Therefore, per capita green space area, green coverage rate of built district, domestic garbage treatment rate, and wastewater treatment rate are included in the urbanization evaluation system to reflect the urban greening construction and waste treatment. In addition, the quality of urbanization has put forward higher requirements on education, medical care, culture, and resident income, so as to improve the level of social security and the quality of resident life. As a result, per capita education expenditure, the number of beds per 1,000 people, and other indicators are included in the social aspects. Finally, considering the five aspects, we construct the corresponding the quality of urbanization index system at city level which contains 18 indicators, as shown in Tab. 1.

The quality of urbanization is measured by panel entropy weight method (PEWM). PEWM can effectively extract the information, avoiding the randomness, presumption and other deviation problems caused by determining the weight due to subjective factors. By this method, the indicator weights are determined based on the full period sample data rather than a single period sample, which makes the data comparable in time dimension. The specific calculation steps are as follows:

Standardization, as shown in Equations (3) and (4)

$$\text{Positive indicator:} A_{tij} = (X_{tij} - \min\{X_j\})/(\max\{X_j\} - \min\{X_j\}) \tag{3}$$

$$\text{Negative indicator:} A_{tij} = (\max\{X_j\} - X_{tij})/(\max\{X_j\} - \min\{X_j\}) \tag{4}$$

Where t is the year, i is the city, j is the index, A_{tij} is the value after standardization, X_{tij} is the initial value. and $\max\{X_j\}$ and $\min\{X_j\})$ represent the maximum and minimum value of the index j in all of the years and the cities studied.

Calculation of the proportion of A_{tij}, as shown in Equation (5)

$$B_{tij} = A_{tij} \Big/ \sum_{t=1}^{m} \sum_{i=1}^{n} A_{tij} \tag{5}$$

Where m and n are total years and total cities, respectively, equal to 11 and 273 in this article.

Calculation of entropy value and difference coefficient, as shown in Equations (6) and (7)

$$C_j = -\frac{1}{\ln mn} \cdot \sum_{t=1}^{m} \sum_{i=1}^{n} B_{tij} \cdot \ln(B_{tij}) \tag{6}$$

$$D_j = 1 - C_j \tag{7}$$

Where C_j denotes the entropy value of index j, D_j denotes the difference coefficient of index j.

Calculation of weight of each index and quality of urbanization, as shown in Equations (8) and (9)

$$W_j = D_j \Big/ \sum_{J=1}^{r} D_j \tag{8}$$

$$OQU_{tij} = \sum_{j=1}^{r} W_j \cdot B_{tij} \quad (9)$$

Where r is the total number of indexes, equals to 18 in this paper, W_j denotes the weight of index j, OQU_{tij} denotes the original value of quality of urbanization. Since the value is too small, we enlarged it (multiply 1000) and obtained the final quality of urbanization (QU).

Table 1. Evaluation system of urbanization quality.

Index I	Index II	Weight (%)	Unit
Population urbanization	X_1: Urban population density	35.44	Person/square kilometer
	X_2: Proportion of urban district population	35.40	%
	X_3: Proportion of employees in secondary and tertiary industries	0.40	%
Economy urbanization	X_4: Per capita GRP	1.81	Yuan
	X_5: Proportion of GRP of secondary and tertiary industries	1.18	%
	X_6: GDP density of secondary and tertiary industries	7.66	10 thousand yuan/km^2
Space urbanization	X_7: Proportion of built-up area	7.00	%
	X_8: Per capita built-up area	0.78	Square meter
	X_9: Per capita living area in urban	0.54	Square meter
	X_{10}: Per capita road area in urban	0.79	Square meter
Environment urbanization	X_{11}: Per capita green area	0.48	Square meter
	X_{12}: Green coverage rate of built-up district	0.09	%
	X_{13}: Domestic garbage treatment rate	0.06	%
	X_{14}: Wastewater treatment rate	0.14	%
Society urbanization	X_{15}: Per capita education expenditure	2.13	Yuan
	X_{16}: Medical facility beds per 1,000 people	0.98	Set
	X_{17}: Books in public libraries per 100 people	4.51	Piece
	X_{18}: Average salary of urban employees	0.95	Yuan/Person

3.2. Empirical model selection

The empirical estimation strategy to test our hypothesis is as follows. Firstly, considering the wide spatial correlation among cities from the perspective of high-speed rail network, this paper selects the spatial econometric model to test Hypothesis 1. In order to compare the differences with the non-network and local perspective, the dummy variable and absolute centrality of high-speed rail have also been introduced. Different control variables and spatial weight matrices are included to ensure the robustness of the empirical results. Secondly, the idea of rolling window regression is used to test hypothesis 2. Considering the length of sample data and the span of high-speed rail construction, we conduct stepwise regression with 3, 4 and 5 years as windows on the basis of spatial econometric model. Thirdly, we screen urban agglomeration cities according to China's 14th Five-Year Plan and performed sub-sample regression to further test whether the impact of high-speed rail networks on the quality of urbanization varies with urban agglomeration development policies (ie, Hypothesis 3).

3.2.1. Spatial econometric model

The choice of spatial econometric model in this paper is based on the following two considerations: First, since we describe the characteristics of the HSR network by the links established between cities through high-speed railway, it is high likely that the HSR network will have a spatial correlation effect on the quality of urbanization. Second, the index of urbanization quality is a composite index that widely covers various aspects of urban development, which may have serious endogenous problems with other variables. The spatial econometric model generally uses maximum likelihood estimation (MLE) or generalized method of moments (GMM), which can help to overcome this problem. Its specific form is as follows:

$$QU_{it} = \rho W \cdot QU_{jt} + \beta X_{it} + \delta W \cdot X_{jt} + \mu_i + \gamma_t + \varepsilon_{it} \tag{10}$$

Where i, j, and t denote city i, city j, and year t, respectively; QU is the quality of urbanization; X includes the core explanatory variable HSR and other control variables; W is the n × n spatial weight matrix describing the spatial relation of cities, n is the number of cities; Both ρ and δ are spatial spillover coefficients to evaluate the impact of city j on city i while β only measures the impact within a city; μ_i, γ_t and ε_{it} denote individual effect, time effect and random error, respectively.

About the setting of W, we adopt two matrices in accordance with spatial adjacency and geographic distance. For adjacent distance weight matrix W_1, the spatial weight of two cities with adjacent relation is set to 1, and vice versa to 0 [49]. Noticeably, a diagonal element is 0, too. For the geographic distance weight matrix W_2, the element w_{ij} is calculated as Equation (11):

$$w_{ij} = \frac{1/D_{ij}}{\sum_{j=1}^{N}(1/D_{ij})} \tag{11}$$

Where D_{ij} is the geographic distance between the city i and j. The value is calculated from city's latitude and longitude data, which obtained from the 1:4 million terrain database of the National Basic Geographic Information System. Since the weights in W_1 are relatively simple, we will use W_2 for empirical analysis and W_1 for a robustness test.

3.2.2. Control variables

The selection of control variables is based on the following aspects.

(1) Technology support: Quality of urbanization pursue the intellectualization transformation and development. In this process, new-technology such as IT and DT, can play a key role. These technological innovations are closely related to primary work and produce a systemic change [50], which can transform life and work within a city significantly and fundamentally [51]. Thus, corresponding technology support is an important factor of urbanization development. In this study, the proportion of science and technology expenditure is used to reflect the government's support for science and technology innovation.

(2) Financial development: A stable capital chain and sustainable financial services can promote the expansion of reproduction activities in small and medium-sized enterprises by encouraging innovative activities, preventing monopoly and forming a good market competition environment [52]. In the past, due to the backward of China's investment and financing systems, urbanization quality has long been hindered by a capital bottleneck [53]. Thus, development of financial industry can help to realize the further improvement of urbanization. According to Han et al. [54], the level of financial development is measured by the total loan balance of all financial institutions divided by gross regional product.

(3) Market factors：The market is one of the most active parts of urbanization quality. The total retail consumption of the market divided by gross regional product is a reflection of the marketization degree. The higher the consumption, the more active the market. An active market is conducive to improving transaction efficiency and promoting economic development [55].

(4) Foreign direct investment: Foreign direct investment (FDI) can help to introduce the foreign advanced technology, talents, and management experience, improving the quality of city development [56]. In addition, the frequent communication with the foreign can also improve the reputation of the city, which accelerates the process of urbanization and internationalization. In this

study, FDI is measured by the total amount of foreign investment actually utilized divided by gross regional product.

3.3. Sample and data

The sample includes 273 cities in China for the period 2009-2019, covering all prefecture-level cities and municipalities in mainland China except Tibet and 12 cities with severe data deficiencies. A few missing value data are processed by exponential smoothing method or mean value. In terms of sample interval selection, most scholars agree that 2008 was the first year of HSR opening in China, but we choose 2009 as the starting point for two reasons: first, as a major infrastructure construction, the effect of HSR often has a lag, so we treat all HSR opening years with a lag of half a year. Second, after that, only one HSR line (Nanjing to Hefei) opened in 2008, which cannot be regarded as "network". In addition, since China suffered from a "covid-19" epidemic shock and strict mobility restrictions in 2020, which do not reflect the true benefits of high-speed railway, the data for that year are excluded. The HSR data are from the China Railway Yearbook from 2008 to 2019. Other data are collected from the China City Statistical Yearbook, China Regional Economic Statistical Yearbook, China Urban and Rural Construction Statistical Yearbook and provincial yearbooks. Table 4 shows the descriptive statistics for all variables.

Table 2. Descriptive statistics of various variables.

Variable	Economic implications	N	Unit	Mean	Std. dev	Min	Max
qu	quality of urbanization	3003	-	0.1809	0.1870	0.0176	2.7341
hsr_dum	high-speed railway dummy	3003	-	0.4179	0.4933	0.0000	1.0000
hsr_l	high-speed railway lines	3003	-	0.6044	0.8911	0.0000	6.0000
hsr_rdc	relative degree centrality	3003	%	0.7269	1.2490	0.0000	16.6670
hsr_adc	absolute degree centrality	3003	-	0.8578	1.1538	0.0000	6.9187
hsr_rbc	relative betweenness centrality	3003	%	2.2888	5.3738	0.0000	45.7290
hsr_abc	absolute betweenness centrality	3003	-	269.4749	724.5421	0.0000	8738.812
rtec	technology support	3003	%	0.0026	0.0024	0.0001	0.0415
rfin	financial development	3003	%	2.3732	6.4232	0.0044	128.5692
rmar	market factors	3003	%	0.3812	0.1083	0.0264	1.0126
rfdi	foreign direct investment	3003	%	0.0180	0.0198	0.0000	0.4599

4. Empirical results

4.1. The spatio-temporal evolution characteristics of HSR network

Table 3 shows the development of HSR network in the first 19 HSR cities in 2009 and 2019, including the number of HSR lines, relative degree and betweenness centrality. In terms of cities, China's high-speed railway network mainly originates from metropolis, including two municipalities (Beijing and Tianjin), seven provincial capital cities (Shijiazhuang, Wuhan, Jinan, etc.) and cities with strong economic strength such as Qingdao, Zibo, Weifang (the top 40 of GDP), while 7 medium and small cities (out of 100 in GDP) are embedded in the HSR network. In terms of HSR lines, in addition to Yangquan, Jinzhou, Huludao, Liu'an four small cities, other cities have opened two or more high-speed rail lines. Hefei, Jinan and other metropolis have opened four high-speed rail lines, while

Tianjing, Nanjing and Shenyang even have reached five. Only from the absolute number of HSR lines, the results clearly show that large cities gain the most from the HSR networking process. However, in the global network perspective, the result takes a shocking reversal. In terms of relative degree centrality, the absolute advantage of the lines does not translate into an absolute advantage of the network location. The relative degree centrality of all cities tends to decrease and eventually converge. This is not a local phenomenon, and the decline of national average (from 8.77 to 1.11) and variance (from 3.85 to 0.51) also strongly supports this result. According to the Equation (1), it can be well explained from the speed and layout of China ' s HSR construction. (1) China 's HSR network has expanded very rapidly, with an average of 20 cities opening high-speed rail each year, significantly increasing the base of HSR network nodes (2) Most of China's HSR lines are long-distance inter-provincial lines such as the Beijing-Shanghai line (through 3 municipalities and 4 provinces) and the Beijing-Kowloon line (through 2 municipalities and 7 provinces), which have many stations but a single connection. In terms of betweenness centrality, the law seems not so obvious. Some cities have obvious line advantages (e.g., Hefei), but the degree centrality is much lower than that of single-line cities (e.g., Huludao). One possible explanation is that these cities have a critical geographical location or are located in mandatory routes. Both results show that the absolute amount of HSR infrastructure (such as HSR lines) is not a complete reflection of the importance of the city's location, which supports our improved measurement.

Figure 1 shows the spatial distribution of changes in location importance in relative degree and betweenness centrality from 2009 to 2019. In order to more clearly present the dynamic change process, we further equate this period into three time points, 2009, 2014, and 2019. The evolution of relative degree centrality is shown in (a)-(c) of Figure 1, while (d)-(f) demonstrate the evolution of relative betweenness centrality. From these maps, some conclusions can be drawn: (1) In terms of overall evolutionary trends, the development of China's high-speed railway has gone through three major spatial evolution stages, namely "point distribution - corridor distribution - network distribution". The locational position of HSR cities is becoming more and more balanced. We can see that in the period 2009-2014, most of the cities have increased their locational importance (both degree centrality and betweenness centrality) due to the opening of high-speed railway. During this period, along the four horizontal and four vertical HSR trunk lines, a clear agglomeration of high-location cities has been formed. However, with the further expansion of the HSR's scale from 2014 to 2019, the locational advantages of these cities are rapidly fading. (2) From a regional perspective, both degree centrality and betweenness centrality are higher in cities in the Eastern and Central regions, indicating that the eastern and central regions are the pivotal zones for the development of high-speed railway. (3) For changes in two types of centralities, relative degree centrality continues to decline, but relative intermediary centrality is rising. This means that more and more high-speed railway cities are playing the role of "interchange" rather than "destination", and the role of each city in the high-speed railway network will become more and more prominent.

Table 3. HSR development in the initial HSR cities.

City	hsr_l		hsr_rdc		hsr_rbc	
	2009	2019	2009	2019	2009	2019
Beijing	1.0000	3.0000	5.5560	1.5000	0.0000	3.1010
Tianjing	1.0000	5.0000	5.5560	2.0000	0.0000	20.1610
Shijiazhuang	1.0000	3.0000	5.5560	2.0000	0.0000	10.9280
Qinhuangdao	1.0000	2.0000	5.5560	1.0000	0.0000	17.7990
Nanjing	1.0000	5.0000	5.5560	3.5000	0.0000	45.7290
Hefei	2.0000	4.0000	11.1110	1.0000	1.9610	5.0090
Wuhan	1.0000	2.0000	5.5560	3.0000	0.0000	9.7540
Huanggang	1.0000	2.0000	11.1110	1.5000	1.9610	4.0860

Ji'nan	1.0000	4.0000	5.5560	2.0000	0.0000	23.8520
Qingdao	1.0000	4.0000	5.5560	1.5000	0.0000	4.5030
Zibo	1.0000	2.0000	11.1110	1.5000	1.3070	6.1910
Weifang	1.0000	2.0000	11.1110	1.0000	1.3070	5.3370
Taiyuan	1.0000	3.0000	5.5560	1.5000	0.0000	6.5380
Shenyang	1.0000	5.0000	5.5560	3.0000	0.0000	9.0960
Panjin	1.0000	2.0000	16.6670	2.5000	1.9610	7.8020
Yangquan	1.0000	1.0000	11.1110	1.0000	0.6540	6.3740
Jinzhou	1.0000	1.0000	11.1110	2.0000	0.0000	7.9510
Huludao	1.0000	1.0000	16.6670	1.5000	1.9610	17.0950
Liu'an	1.0000	1.0000	11.1110	1.0000	2.6140	4.4090
national mean	1.0526	1.6244	8.7722	1.1117	0.7224	5.2822
national sd	0.2294	1.0107	3.8470	0.5128	0.9470	7.6108

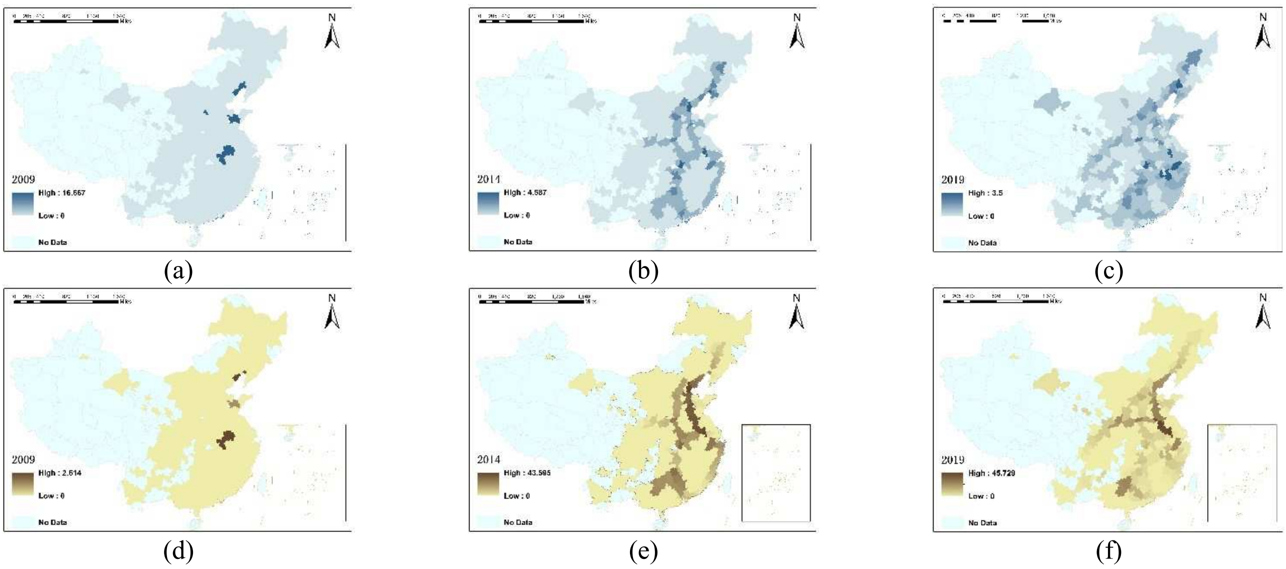

Figure 1. Spatial distribution of centrality change from 2009-2019.

4.2. Spatial autocorrelation test and model determination

This paper examines the spatial agglomeration characteristics and evolution trend of urbanization. As shown in Tab.4, Moran's I value are all significantly positive at the 1% level, showing that China's urbanization quality has significant positive autocorrelation during 2009-2019. From the development trend, we can also find that the positive effect is gradually strengthened. This means that China's overall development is more closely linked in space, and the cross-influence of urban development is stronger.

For the selection of best models, at first, the Lagrange Multiplier (LM) and robust LM tests are adopted to examine whether SEM or SLM is more accurate [57]. Both models have been proved to be appropriate for the regression analysis. Then, we run a further LR & Wald test and discovered that neither SEM nor SLM cannot nested in SDM. So, SDM is more representative. Additionally, the P-value in Hausman test was 0.0000, showing that FE model is more appropriate in this case. Combining with above test results, we construct a spatial Durbin regression model with individual and time fixed effects for all our estimations in this paper.

Table 4. Moran's I of the quality of urbanization in China.

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Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Moran's I	0.055	0.052	0.058	0.054	0.055	0.055	0.062	0.061	0.065	0.047	0.063
P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: the global autocorrelation test results are based on the geographical distance weight matrix.

4.3. HSR network and the quality of urbanization

We use five HSR proxy variables including dummy variables, absolute and relative degree centrality, absolute and relative betweenness centrality to test the impact of high-speed railway on urbanization quality from non-network, local network and overall network. Cities with a higher centrality indicate a higher importance in the HSR network.

Table 6 reports the estimation results of the whole sample with a MLE method. Odd and even models represent regression results without and with control variables respectively. In models (3)-(6), the coefficients of hsr_rdc and hsr_adc are both negative, suggesting that increase in degree centrality is detrimental to improving the quality of urbanization. Among them, coefficients of hsr_rdc have passed the test of significance at the 1% level while coefficients of hsr_adc does not, further indicating that location changes in global network have a more pronounced impact on the quality of urbanization than changes in local network. In models (7) -(10), the coefficients of hsr_rbc and hsr_abc are both positive, showing that rising betweenness centrality is conducive to promoting the urbanization quality. Of these, only one of the four models, model (10) has passed the significance test and the estimated coefficient of hsr_abc was just 0.0001, demonstrating that the effect of locational change arising from betweenness centrality on urbanization is limited. Since the HSR network actually reduces the relative degree centrality and improves the relative betweenness centrality, all above results show that HSR network can indeed enhance the quality of urbanization. This well verifies hypothesis 1. Meanwhile, by comparing the regression results of models (5) and (8), we can also see that the direct connectivity effect of HSR network would be more pronounced than the intermediary effect. However, it is worth wondering why a decline in the importance of a city drives urbanization instead.This can be explained as follows: With the expansion of high-speed rail network, the line advantage of a single city, especially the HSR hub city (with more lines), will be gradually diluted, which makes the siphon effect of large cities gradually weakened, and the majority of small and medium-sized cities usher in a good opportunity for development [58]. Due to ignoring this dilution effect, the positive effect of high-speed rail has not been effectively reflected in the perspective of non-network and local network. The coefficients of hsr_dum in model (1) and (2) even reache a completely opposite conclusion. Thus, all the evidence demonstrates the necessity of relative index measurement again.

Regarding the impact of control variables, estimation results shows that only the coefficient of rtec is significantly positive across all models. This means that technical support has a relatively stable role in promoting the quality of urbanization, whether based on the network perspective or non-network perspective. Technological innovation often relies on breakthroughs in basic scientific research, so it can result in a systemic rather than a unilateral change [50]. Therefore, for an urban system, the improvement of technological level can promote its overall development from multi-aspects.

Table 6. The result of overall regression.

Variables	Dependent variable: Quality of urbanization									
	hsr_dum		hsr_rdc		hsr_adc hsr_rbc				hsr_abc	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
hsr	-0.0087**	-0.0097***	-0.0052***	-0.0047***	-0.0001	-0.0010	0.0002	0.0004	0.0001	0.0001**
W×hsr	0.0326***	0.0067	0.0384***	0.0198*	0.0100***	-0.0055	0.0014*	-0.0007	0.0001	-0.0001**

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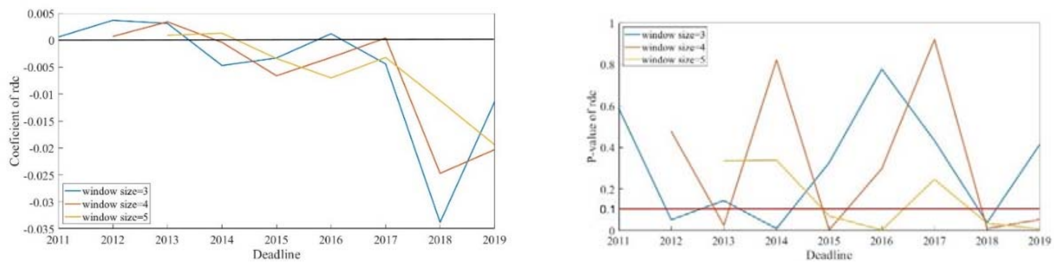
rtec		4.1260***		4.1080***		4.1606***		4.1530***		4.0645***
rfin		0.0000		0.0000		0.0000		0.0000		0.0000
rmar		-0.0788***		-0.0806***		-0.0807***		-0.0808***		-0.0841***
rfdi		-0.2950***		-0.2940***		-0.2903***		-0.2910***		-0.2821***
rho	0.6600***	0.2800**	0.7770***	0.2810**	0.6686***	0.2858**	0.7640***	0.2880**	0.7471***	0.2939**
sigma2	0.0031***	0.0030***	0.0031***	0.0030***	0.0031***	0.0030***	0.0031***	0.0030***	0.0031***	0.0030***
city FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730
logL	4008.9755	4059.2649	4011.5885	4062.8970	4005.8872	4056.2412	4002.2400	4056.5197	4003.6787	4059.3856
Vif	1.0000	1.1100	1.0000	1.0700	1.0000	1.1100	1.0000	1.0700	1.0000	1.0700
LM-sar	226.672***	89.904***	679.041***	176.317***	222.179***	86.823***	616.320***	165.752***	604.148***	170.270***
(Robust)	0.475	7.478***	54.134***	3.527***	1.536	10.985***	10.747***	0.543	44.508***	0.768
LM-sem	484.604***	357.409***	627.286***	277.912***	523.487***	393.390***	636.837***	311.785***	641.398***	309.710***
(robust)	258.407***	274.983***	2.378	105.122***	302.844***	317.553***	31.264***	146.576***	44.508***	140.208***

Notes: * P < 0.1. ** P < 0.05. *** P < 0.01.

4.4. HSR network and the quality of urbanization: dynamic analysis

The rolling-window regression is applicable when the correlation between variables is time-varying. This method divides the whole sample into several sub-samples by setting a fixed rolling window (time span T), and then examines the impact of each period separately. Drawing on this idea and combining with the spatial econometric model, this paper examines the dynamic impact of the HSR network on the quality of urbanization in one-year steps. Since Table 6 shows that the mediating effect of the HSR network is not significant, this section only explores the direct effect (i.e., relative degree centrality). To visually verify the presence of a nonlinear characteristic, we present the estimation results including coefficients and significance for all HSR variables in the form of line graphs.

Figure 2 reports the rolling regression results of the impact of the HSR network on urbanization at different window size settings. As shown in Figure 2a, the estimated coefficients under all windows show a clear downward trend (from positive to negative to smaller negative values), indicating that the HSR network does have a non-linear effect on the quality of urbanization. This finding supports our hypothesis 2.



(a) (b)

Figure 2. Estimated coefficients and significance under different rolling-windows. Note: The horizontal axis time indicates the year ending at that window size.

Specifically, at the beginning of the construction of the HSR network, the increased importance of cities in the HSR network is conducive to promoting urban development. This can be interpreted as a "leader advantage", where the first cities to open high speed railways (often large cities) have an extremely obvious transportation and location advantage over other cities, so resources tend to flow to these cities, creating a stronger centripetal force effect [6]. This conclusion has been validated by most studies [59,60]. However, as more and more cities are connected to the HSR network, this centripetal effect is gradually weakening and being replaced by a centrifugal effect [61]. High-speed rail is no longer the "patent" of large cities. A more equitable distribution of transport resources fully mobilizes the development of small and medium-sized cities and promotes balanced regional development [62]. More importantly, this centrifugal force effect will be further strengthened with the further expansion of the size of the high-speed rail network. All these findings provide strong evidence for the new economic geography theory [45].

Based on the above estimation results, we can roughly divide the process of China's HSR network into three periods. From the results of Figure 2b, these three periods can be further identified as: 2010-2012, 2013-2015, and 2016-2019 with estimated coefficients of +0.0037, -0.0066, and -0.0203, respectively. The corresponding HSR coverage ranges are 0-25.27%, 33.33%-53.48%, and over 61.17%, respectively, showing a strong "stage characteristic" of HSR network development. However, it is worth noting that when data in 2019 are added to the sub-sample interval, the estimated coefficient rebounds significantly, indicating that the centrifugal force effect is also weakening to some extent. As shown in table 7, there are only 11 new HSR cities in 2019, the second-lowest of all years. This means that the size of China's HSR network (number of nodes) has gradually stabilized and its scale effect is diminishing. In conclusion, our study shows that network size does play a crucial role in the impact of HSR on urban development, rather than being a negligible factor.

Table 7. The HSR cities and coverage from 2009 to 2019.

YEAR	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
HSR cities	19	41	57	69	91	110	146	167	172	186	197
New HSR cities	19	22	16	12	22	19	36	21	5	14	11
HSR coverage	0.07	0.15	0.21	0.25	0.33	0.40	0.53	0.61	0.63	0.68	0.72

Notes: The total number of cities is equal to 273

4.5. HSR network and the quality of urbanization: main beneficiaries

The improvement of transportation conditions has strengthened the cross-regional links as China's urbanization progresses. To boost urbanization quality and regional core competitiveness, China has proposed Urban Agglomeration Development Strategy. The strategy emphasizes coordination between neighboring cities in the vicinity, which fits well within the comfort zone of high-speed rail travel. Thus, for verifying its policy effect, this paper divides 273 cities into 208 urban agglomeration cities and 65 non-urban agglomeration cities according to the 14th Five-Year Plan. The estimated results are shown in Table 8 below.

From the results, urban agglomeration development strategy has proved useful. Firstly, the estimated coefficients of hsr_rdc in Model（1）and Model (2) are statistically negative, whereas the estimated coefficients of hsr_rdc in Model (5) and Model (6) are not significant. It shows that the decline of HSR relative degree centrality has a negligible impact on the growth of urbanization quality in non-urban agglomeration cities, but a considerable benefit for urban agglomeration cities. As a result, the development of HSR network will be more conducive to urban agglomeration cities, rather than non-urban agglomeration cities. Furthermore, the estimation coefficients of hsr_rbc in Model (4) and Model (8) are significantly positive and negative, respectively. This means that the HSR mediating effect can promote the development of urban agglomeration cities but inhibit the development of non-urban agglomeration cities. So, by comparing the regression results of two HSR network variables, we can see that both degree centrality and intermediary centrality have proved that this model of urban agglomeration development may benefit more from the HSR network, which is consistent with the conclusions of Yin et al. [36]. This heterogeneity can be explained from two aspects. First, urban agglomeration cities often have higher economic level and larger population

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size, and their demand for HSR travel is stronger, so the positive effect may be more obvious. Secondly, due to the unity of urban agglomeration development policy, the cooperation between urban agglomeration cities is stronger, and its factor allocation will be more reasonable. This will be more helpful to high-speed railway connecting regional economic activities into a whole, encouraging knowledge spillover within urban agglomerations, and thus promoting innovation and economic growth [27]. So, HSR effect will be more fully reflected in the model of urban agglomeration development. All evidence supports the hypothesis 3.

Table 8. The result of urban agglomerations and non-urban agglomerations.

Variables	Dependent variable: Quality of urbanization							
	Urban agglomerations				Non-urban agglomerations			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
hsr_rdc	-0.0064***	-0.0058***			-0.0001	0.00001		
hsr_rbc			0.0005	0.0007*			-0.0013***	-0.0012***
W×hsr	0.0350***	0.0228*	0.0012	-0.0001	-0.0007	-0.0030	0.0046***	0.0020**
LR_hsr	0.1080***	0.0231	0.0063*	0.0008	-0.0037	-0.0037	0.0075***	0.0010
Con-var	No	Yes	No	Yes	No	Yes	No	Yes
N	2080	2080	2080	2080	650	650	650	650
LogL	2792.262	2835.499	2784.876	2830.721	1819.698	1855.436	1850.296	1873.345
Vif	1.00	1.06	1.00	1.07	1.00	1.06	1.00	1.06
LM-sar	264.184***	96.496***	331.252***	94.750***	90.643***	41.965***	76.983***	35.990***
(Robust)	42.021***	0.000	2.567	0.217	17.562***	46.500***	40.031***	41.224***
LM-sem	356.750***	168.177***	338.356***	176.333***	84.544***	18.803***	63.791***	14.836***
(Robust)	137.587***	71.681***	9.671***	81.8000***	11.463***	23.337***	26.839***	20.070***

Notes: * P < 0.1. ** P < 0.05. *** P < 0.01

4.6. HSR network and the quality of urbanization: robustness test

Regarding the robustness test, scholars often choose lagged variables and proxy variables to replace the original variables, or change the time length of the sample. However, these methods are not applicable in this paper for two reasons. (1) Centrality is a proprietary measure of node importance in network analysis and is difficult to substitute. (2) Our study emphasizes the heterogeneity of the temporal dimension. Therefore, we still draw on the approach commonly used in spatial econometric analysis, which is to replace the spatial weight matrix, to perform robustness tests. In this paper, another spatial weight matrix is the adjacency matrix. The results of all sample and sub-urban agglomerations based on adjacent distance weight matrix are shown in table 9. From the result, we can find that almost all coefficients do not change in sign. As a result, the empirical findings can be considered reliable.

Table 9. The regression result based on adjacent distance matrix.

variables	Dependent variable: Quality of urbanization							
	overall regression					Urban agglomerations		Non-urban agglomerations	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
hsr_dum	-0.0068*								
hsr_rdc		-0.0061***				-0.0061***		-0.0009	
hsr_adc			-0.0008						

hsr_rbc				0.0007***			0.0011**		-0.0009***
hsr_abc					0.0001***				
W×hsr	0.0294***	0.0095***	0.0118***	0.0002	0.0001	0.0088***	0.0002	0.0032***	0.0012***
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
city FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	2730	2730	2730	2730	2730	2080	2080	650	650

Notes: * $P < 0.1$. ** $P < 0.05$. *** $P < 0.01$.

5. Discussions and conclusions

In this paper, we apply the improved social network analysis method and the panel entropy weight method to measure the importance of cities in the HSR network and their urbanization quality, respectively. After that, using spatial econometric model and rolling window regression idea, we empirically test the impact of the HSR network on the quality of urbanization and its dynamics over the period 2009-2019. On this basis, we further explore who are the main beneficiaries of HSR networking in terms of city cluster classification. All conclusions are drawn as follows. (1) The HSR network can significantly contribute to the improvement of urbanization quality, and the direct effect of the network is stronger than the intermediary effect. The positive effect is due to the dilution effect of the increased network size, which promotes the equality of cities in the HSR network. (2) The impact of HSR network on urbanization quality shows a marginal increasing trend and obvious periodic characteristics over time. Depending on the coverage of HSR cities, the impact can be roughly divided into three stages, inhibition (0-30%), relatively weak promotion (30%-60%) and relatively strong promotion (more than 60%) (3) The impact of HSR network on urbanization quality is urban heterogeneous. Urban agglomeration cities will benefit more from HSR network, while non-urban agglomeration cities will be at a relative disadvantage. In addition, we also innovatively find an inverted "U" feature in the evolution of urban centrality.

With the rapid development of high-speed rail networks, especially in China, there is a large number of studies on the impact of HSR infrastructure construction on urban development. However, few studies have considered the impact of network structure, let alone changes in network size. Our study, based on a dynamic network perspective, nicely fills this gap, which not only validates the existence of "network effects", but also provides a more plausible explanation for the coexistence of two controversial views (positive and negative effects of HSR) from differences in network size. In addition to its academic value, this study has important policy implications for future HSR layout and the improvement of urbanization quality in China and other countries.

First, China should expedite the transition of its development power and drive urban growth by technological innovation. In the current stage, the demographic dividend of Chinese economic development is fading as fertility declines and population ages [63]. If the Chinese government wishes to achieve high-quality urbanization while maintaining rapid economic growth, the improvement of individual labor conversion rate and other factors' participation will be necessary. Our empirical results show that technical support is the most stable positive factor contributing to the quality improvement of urbanization, so it is still very necessary for the government to continue to increase the investment funding for research and technology.

Second, the government should formulate and adjust its policies according to the different stages of the development of the HSR network. For example, in the early stages of HSR network construction, large cities will have a very significant siphoning effect on the surrounding small and medium-sized cities. At this point, policies such as strict population mobility and household registration restrictions are very necessary. But when the coverage reaches a high level, these policies should be adjusted in time to ensure the healthy development of large cities due to the gradual increase of centrifugal force effect. Specially for China, the network scale effect is beginning to show its weakness. With the completion of the "eight vertical and eight horizontal" high-speed railway plan, the scale of the HSR network (the number of nodes) has basically stabilized, but the number of connections still has a huge upside. As a consequence, the key to future HSR layout and city competition lies in how to effectively connect HSR cities to each other. Our research shows that HSR has both positive and negative effects. Therefore, cities should reasonably plan the high-speed rail network according to local endowment conditions to give full play to the positive side of the high-speed rail effect [64].

Third, urban agglomeration growth paradigms should be appreciated and broadly popularized. In the urban agglomeration development model, the advantages of HSR network can be further reflected and better utilized. Governments at all levels need to formulate a unified and complementary development plan based on the factor endowment and technological level of each city in the urban agglomeration. Satellite cities and other surrounding cities should provide corresponding support for the development of core cities and help to enhance the competitiveness of core cities, including the integration of regional transportation, more huge market foundation and financial support. In return, the core city should actively promote the characteristic industry growth of neighboring cities and build a comparative advantage. All urban agglomeration cities eventually are mutually beneficial and form a virtuous loop.

However, there are still some limitations in this study. First, due to data constraints, we do not use a complete rolling window regression method, but only draw on the idea. In the empirical process of our dynamic impact, we lack the coefficient stability test (such as Sub-F, Mean-F and Exp-F test), and the window setting value is far less than the minimum value of 20. Second, although we have adopted maximum likelihood estimation and fixed effect model to alleviate endogeneity, it is still difficult to be completely eradicated. This is because the urbanization quality index covers all aspects of social and economic development, and has a general two-way causal relationship with independent variables. Third, this paper does not explore the causal relationship between HSR network and urbanization quality, but only considers the correlation relationship, which may reduce the credibility of the explanation. These issues require further refinement of empirical tools and more in-depth research.

Author Contributions: Jingyu Chen: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. Weidong Li: Conceptualization, Methodology, Project administration, Funding acquisition, Writing – review & editing. Bingyu Wu: Conceptualization, Methodology, Writing – review & editing, Data curation, Formal analysis. Zhen Yu: Conceptualization, Writing – review & editing, Data curation, Formal analysis.

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Conflicts of Interest: The authors declare that they have no conflicts of interest.

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