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Does Urban Agglomeration Promote the Development of Cities? Evidence from the Urban Network Externalities

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Abstract: This paper discusses whether urban agglomeration can promote urban growth from the perspective of network externalities. Although agglomeration externalities play an important role in promoting regional development, improved accessibility makes urban network externalities an influential force in reshaping regional economic growth. This paper identifies the urban network based on the data of train frequency and travel time data among 271 cities in China. Then, the spatial Durbin model is used to investigate the effect of urban agglomeration on economic growth from the perspective of urban network externalities. The results demonstrate that there are significant network externalities among cities in China, which play a pivotal role in boosting urban growth. Interactions among cities produce cross-regional spillovers, causing network externalities to no longer be dependent on geographical proximity. This is significantly different from agglomeration externalities that are limited to a certain regional scale. As the scope of the urban network expands, network externalities become more pronounced. Different regional characteristics all lead to heterogeneous results of network externalities. The construction of high-speed railways, as well as the well-developed urban network system, strengthen the positive impact of network externalities. Smaller cities benefit more from higher-level urban networks than regional networks.

Keywords: urban agglomeration; urban network externalities; spatial econometrics

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1. Introduction

Nowadays, China's urbanization process has stepped into the high-quality growth phase. Regional economic structures such as urban agglomerations and metropolitan areas centered on core cities progressively become major spatial carriers and cornerstones to support economic growth. With the construction of high-speed railway (HSR) networks and the rapid development of communication technology, the cross-regional flow of production factors such as labor and capital among cities has been significantly enhanced and the connection between economic entities and cities has become closer, prompting the gradual formation of an urban network containing different numbers of small, medium and large cities. The reform in enterprise organization and the rapid development of the modern productive service industry create more opportunities for intercity communication, while the degree of regional division of labor and collaboration continues to improve. The trend of urban networking, which is established by combining different spatial scales such as metropolitan areas, urban agglomerations, and large, medium and small-sized cities, is increasingly prominent. This makes the agglomeration economy work in a broader spatial scope. The deepening of intercity ties and the increased frequency of exchanges has also led to the gradual integration of more cross-regional companies and cities into urban networks. The market mechanism, culture, and system in the region have profoundly shaped the structure pattern of urban networks, which makes the cross-regional spatial spillover effect play a more significant role in economic growth.

Due to the existence of urban network externalities, urban development is not only associated with the functions and characteristics of cities themselves but also depends on the interconnection and spatial spillover effects between cities [1–3]. In other words, cities do not exist in isolation. With the promotion of regional integration and networking development trends, scholars' research on urban and regional development is no longer limited to geographic proximity, but breaks through the limitations of geographic distance and shifts the perspective from geographic proximity to urban network connection [4,5]. Geographically non-contiguous entities can generate economic externalities as a result of the interactions, so geographical proximity is not the only source of externalities [6]. Nowadays, the research of urban network externalities has attracted widespread attention from scholars, and its impact on urban economic growth has become a hot issue in urban and regional research [1–3,6].

In general, several empirical studies in the existing literature investigate the influence of urban agglomeration on urban economic performance from the viewpoint of urban network externalities. Several studies point to the existence of network externalities [5,7]. Others use the social network approach to assess the positive impact of increased urban connectivity and accessibility on urban growth due to the construction of high-speed rail networks [8–12]. In this paper, we use train schedule data to construct urban networks based on two dimensions, flow volume and structure position, which are used as the spatial matrices to examine the spillover effects of urban agglomeration and the effects of network externalities on urban growth. While traditional spatial matrices mostly use an adjacency matrix or inverse distance matrix, this study constructs one by integrating interconnections across cities to provide a new explanation for the agglomeration spillovers. Second, inconsistent conclusions are obtained when investigating the relationship between urban agglomeration and economic growth in isolation from the influence of spatial scale [13]. Furthermore, there are relatively few discussions on the spatial scale influence of network externalities [14–16]. This paper is dedicated to examining the economic growth effects of network externalities and their trends in different spatial scale perspectives.

2. Literature Review

2.1. Urban Agglomeration, Agglomeration Externalities and Network Externalities

Urban agglomeration refers to the agglomeration of economic activities in the geographical area. This agglomeration includes the concentration of both population and industries within a given city, but also takes into account the economic activities within the geographic space of the surrounding areas and the corresponding distance factors, that is, the intercity agglomeration process. Conceptually, urban agglomeration is essentially the same as urban clustering and urban conurbation. Since urban agglomeration covers both intra- and inter-urban aspects, this study adopts the concept of urban agglomeration to emphasize it as a dynamic process rather than as an area of urban agglomeration with fixed geographical boundaries. Agglomeration externalities, as the first important tool to explain the formation and development of cities, originate from the synergistic positioning of economic agents and emphasize the advantages of agglomeration due to geographical proximity [17], such as input–output linkages, labor sharing, knowledge spillovers, and other benefits [18–20]. In early research, agglomeration externalities are defined as geographically constrained and assumed to be regionally uninfluential, investigating the role of industrial diversification or specialization on urban growth [21]. In fact, cities are spatially connected. The concentration of economic activities promotes the gradual formation of continuous urban agglomerations in geographically adjacent regions. Cities also form interconnections with the development of infrastructure as well as communication technologies [22], generating network externalities gradually. The agglomeration of economic activities in geographical locations first drives agglomeration externalities, and this agglomeration advantage is transmitted between cities along with the formation of urban networks. Research on the Dutch urban development pattern indicates that these cities either have more functions and larger populations, or stronger relationships with other cities. The conclusions on function and size suggest the importance of agglomeration externalities, while the relationships provide crucial evidence for positive network externalities.

Urban networks refer to the urban spatial organization of cities of different sizes and levels within a certain spatial area through economic and social linkages, and the cooperation and synergy between urban nodes is an important cause of network externalities [2,7,23,24]. That is, the total utility of the urban network composed of interconnected cities exceeds the total utility obtained by adding up the individual cities. Network accessibility is crucial for urban networks as opposed to geographical proximity [1,25]. Due to the limitations of transportation and communication technologies, early interactions between cities relied heavily on geographical proximity. The closer the distance, the more opportunities and the lower the cost of intercity interactions, making it easier for neighboring areas to share in the spillover effects of agglomeration. Small cities gain agglomeration advantages and high-speed growth through the borrowed size generated by neighboring big cities. Nowadays, capital flows and information transfers are no longer based on geographical proximity. The construction of transportation infrastructure has also significantly reduced the travel time between cities, and the interaction between cities is naturally no longer based on geographical proximity but relies on the city network structure [3,26]. Network externalities can occur between cities that are far apart as long as the two cities have a strong interactive relationship [16,27].

Sharing, matching, and learning, as three micro-mechanisms by which agglomeration externalities occur across firms, are also not limited to within a single city [28]. The strong mobility of network structure alleviates the constraints of information frictions in space and distance on economic activities. Driven by intercity functional complementarities and synergistic relationships, micro-entities can further breakthrough administrative boundaries and access diverse and differentiated factors of production. In other words, the three mechanisms mentioned above are equally fundamental to network externalities. Network externalities are considered an extension of agglomeration externalities on a larger spatial scale [26]. Better network connectivity implies a higher level of knowledge access [29], and the mobility of production factors is also enhanced through urban networks, achieving optimal allocation [30]. To sum up, factor allocation, industrial convergence, and functional integration are all important processes that promote regional resource sharing and realize product value enhancement and production efficiency improvement, reflecting the extension of economic activities from enterprise agglomeration to industrial agglomeration and urban agglomeration. Therefore, urban network externality can be summarized as the external economy of all factors flowing through the urban network.

Agglomeration externality focuses on individual cities and applies to a relatively small geographical scale. Although urban network externalities still take individual cities as the basic unit, they treat cities as nodes in urban networks rather than as independent individuals, and nodes generate network externalities due to their interactions. Due to the premise of geographical proximity, agglomeration externalities are usually confined within the administrative boundaries and decay with distance [31], ignoring the fact of cross-regional linkages. Network externalities do not depend on geographical proximity [23], but vary with the intensity of intercity connections [6,24]. As a result, it is not strictly spatially constrained, but focuses more on the functional interactions and economic linkages between cities, highlighting the non-localized influence of cities [24,32,33].

2.2. Urban Network Externalities and Urban Economic Growth

As a result of cities being strongly connected in a network structure, an urban network is not only a spatial organization that induces the optimal allocation of different production factors in a more efficient spatial organization [30], but it is also an influential power that promotes regional economic growth and reduces regional disparities [34–37]. Zhang et al. (2022) [38] quantify urban network externalities in terms of flow volume and structural position using capital flow data from 12 urban agglomerations in China and demonstrate that urban network externalities have a positive impact on regional economic growth. Jiang et al. (2022) [39] distinguish agglomeration externalities from network externalities using investments inside and outside urban agglomerations and confirm that both can significantly contribute to urban economic growth. Li et al. (2021) [33] use the number of strategic emerging firms and their linkages to refer to agglomeration externalities and network externalities, respectively, and demonstrate that network externalities play a more significant role in urban growth. Chen et al. (2020) [40] construct an urban cluster index and reveal that urban clusters exert both spatial agglomeration and network effects. Urban linkages become stronger as the agglomeration degree increases and thus contribute to the improvement of total factor ecological performance.

The impact of network externalities can also show heterogeneity considering spatial scale, city size, and economic development levels [3,41,42]. Typically, large cities are more dependent on national or world urban networks, while small and medium-sized cities benefit from regional urban networks formed by surrounding areas [3,5]. On the other hand, the presence of spatial competition also makes large cities intensify the siphoning effect on small cities, thus undermining their development basis and causing agglomeration shadows [26]. The urban network existing in provinces, urban agglomerations, countries, and even the world has gradually strengthened its functional links. The impact of cities and the urban networks in which they are embedded on economic performance is even greater than that of the size of the cities themselves [22]. In particular, some of the small and medium-sized cities that dominate the urban network have significantly internalized the agglomeration benefits of large cities through borrowed size.

In the empirical studies of HSR and urban network externalities, the economic impact of HSR is mainly achieved by improving intercity accessibility and connectivity, and its contribution to economic growth is mainly shared among cities through network spillovers rather than the isolated presence of HSR facilities [43]. It was found that improved accessibility expands the spatial scale of urban networks and has a positive impact on regional economies at both the regional and national levels [44]. Connectivity works on intercity cooperation, indicating an increase in the flow volume of interaction and the strength of intercity relationships [45]. This further increases the mobility of production factors and resources [43,46], which is more conducive to the optimal allocation within the region and between cities. In addition, HSR networks are beneficial in promoting the agglomeration of economic activities, thus generating stronger agglomeration externalities and therefore also inhibiting the economic growth of marginal cities excluded from the HSR network [47]. Huang et al. (2022) [8] confirm that the network externalities from HSR accelerate urban economic growth by expanding the spatial scope of factor flows and knowledge spillovers and reducing transaction costs. Based on the policy of HSR opening, Tang et al. (2021) [29] demonstrate that it not only promotes factor agglomeration but also strengthens intercity economic linkages, and contributes to the enhancement of knowledge spillovers and urban innovation performance from both agglomeration externalities and network externalities.

In relevant empirical studies in China, scholars mostly use Social Network Analysis to measure indicators such as closeness centrality and betweenness centrality to construct urban networks and investigate their impact on urban economic development with the help of high-speed rail data. Research confirms that urban network externalities depend on network connections formed by HSR construction and play an active role in urban economic development [8]. Further research identifies a threshold effect on the positive impact of urban network location improvement, mainly on core cities [10,11], while the regional development gap and the close connection of high-speed rail can have a marginal locking effect on less economically developed regions [12]. However, there are also studies showing that the construction of the high-speed rail network has a higher contribution to economic development in the western region and small cities. In addition, the marginal contribution of new HSR lines to economic growth is reduced due to the crowding-out effect caused by overconcentration [9].

Most of the empirical studies on urban network externalities only examine the impact of stronger intercity linkages on urban economic performance. However, it is not realized that it is the agglomeration of economic activities and population that underlies the creation of such externalities, even at a small scale. Urban network externalities are considered an extension of agglomeration externalities in a larger geographic space [26], but this is not effectively reflected in the above studies. The spillover effects of economic activities make cities more connected, but most researchers do not examine spatial interrelationships. Instead, the investigation of network externalities requires breaking the concept of proximity in the traditional geographic sense and measuring the spillover effects under urban network relationships. In addition, most studies are based on easily measurable spatial scales, such as one or more city agglomerations or at the national level. Moreover, urban networks present distinctive features such as cross-regionality, mobility, and multi-scale, and their role based on different spatial scales has not been fully discussed.

3. Models and Methods

3.1. Urban Network Construction

Given that urban network externalities are generated based on accessibility, this paper uses the travel time and frequency data of China's railway working diagram to construct the urban network. The train frequency data reflect the intensity of interaction between cities, and the travel time data are used to measure the locational characteristics. The shortening of intercity time distance or the increase in train frequency reflects the enhancement of urban accessibility and connectivity. To calculate the specific situation of railroad operation in each city, this study collects a large amount of train operation information from the website channels such as China Railway Yearbook, China Railway Corporation website, National Railway Passenger Train Timetable, and Railway Customer Service Center 12306. The specific data collection and processing steps are as follows:

First, the data of train operations between different train stations in two cities from among 271 cities in calendar years 2010–2019 were obtained from the railroad operation schedule, including train number, departure station, arrival station, driving time, arrival time, running mileage, and other information. Second, the train driving time and arrival time were combined to calculate the specific travel time between the two stations. The third step was to match the train station with the city. Since there are multiple train stations in some cities and trains may pass through different stations in the same city, it was necessary to match the station sites with specific cities. The fourth step was to filter the data. Since a train may pass through multiple stations in the same city, duplicate data needed to be excluded. The shorter travel time between the two cities was used as the criterion for screening. Finally, we obtained the train running time and train frequency data from 271 cities corresponding to the two cities, totaling 180,462 datapoints. The urban network was constructed using the number of trains and the travel times between cities.

3.2. Empirical Model and Variables

The spatial econometric model can directly identify the existence of network externalities and the effects on urban economic growth by setting up the spatial weight matrix. In addition, the spatial econometric method can minimize the influence of omitted variables in the empirical results to a certain extent. The baseline model is set up as follows:

$$\mathrm{lnrgdp}_{it} = c + \rho\sum_{j=1}^{n} w_{ij}\mathrm{lnrgdp}_{it} + \alpha_1 IC_{it} + X_{it} + \lambda_1\sum_{j=1}^{n} IC_{it} + \lambda_2\sum_{j=1}^{n} w_{ij}X_{it} + \mu_i + \nu_t + \xi_{it} \quad (1)$$

The model takes a double logarithmic form, and the explanatory variable is GDP per capita, which is used to measure the economic growth of the city. IC is the main explanatory variable of urban agglomeration degree, w_{ij} denotes the spatial weight matrix, X is the control variables, μ_i, ν_t represent the individual and time effect, respectively, and ξ_{it} is the random error.

The main explanatory variable is the urban agglomeration degree IC. In previous studies, urban agglomeration is usually calculated from two perspectives: density and size, such as urban population or population density. However, this measurement cannot effectively reflect the spatial location characteristics of cities. For comparability, according to Protnov and Schwartz (2009) [48], the urban agglomeration degree is measured in two dimensions, size and spatial location, which is measured by the ratio of urban spatial isolation IS and remoteness IR.

$$IC_i = IS/IR = \ln(\sum_{i=1}^{n} P_j/IR_{ik}) \quad (2)$$

IS is the scale effect and is measured by the total population within a certain range of the target city i, P_j denotes the population of the jth city within the region. The distance between the target city and the central city is also considered in terms of the structural effect to capture the spatial location characteristics of the city in the urban network. That is the urban remoteness IR, which is measured by the distance between city i and the nearest core city k. In contrast to previous studies, the distance between cities is calculated by temporal distance instead of geographical distance. The distance is the average travel time data between cities. The urban agglomeration index has a low value in scattered areas or peripheral areas distant from the core city and has a high value in densely populated areas or close to the core city. The indicator reflects the characteristics of the network structure of cities to a certain extent by adjusting the size of the relative distance between cities, and measures the degree of urban agglomeration more scientifically.

Population size and economic level are the two criteria for selecting core cities according to Protnov and Schwartz (2009) [48] and Huang et al. (2018) [49]. The total urban population of districts in the city exceeds 1.5 million. The GDP of the city ranks among the top two in its province. To minimize calculation bias caused by data deviations, urban population and economic status are measured using the mean value of the sample period. Under the above criteria, 39 cities are identified as the core cities. Considering the influence of temporal distance on the calculation of the urban agglomeration index and the empirical results, we take one hour as the basis and one half-hour as the increment to calculate the urban agglomeration status under different time distances.

To correctly identify the relation between urban network externalities and urban growth, the control variables are included in the analysis. Capital investment is calculated using the ratio of urban fixed asset investment to GDP. Human capital is calculated using the number of undergraduates per ten thousand people. Foreign direct investment and fiscal expenditure as a share of GDP are used to indicate foreign investment and government intervention, respectively. The city scale is expressed by the number of the permanent population. Innovation capacity is calculated by the patents granted per capita. Urban road area per capita is used to measure the condition of urban infrastructure.

An abundance of different spatial matrices have been used in the empirical economic literature to investigate the spillover effect, such as the adjacency matrix, geographic distance matrix, and economic geographic distance matrix, but the matrix based on geographic linkages cannot reflect the strength of the connection between cities. In the research of Shi et al. (2022) [37] and Zhang et al. (2022) [38], both flow volume and structural position are two essential and important dimensions in urban networks. The former reflects the strength of connections between network nodes, and an increase in flow volume indicates an increase in the frequency of interactions. The latter indicates urban network positionality [36–38,50]. The larger the number of cities clustered within a region, the greater the potential for intercity cooperation and agglomeration. In addition, it is worth noting that higher flow volume does not necessarily correspond to a denser cluster structure and vice versa. In this paper, the spatial weight matrix w_{ij} is constructed using a composite matrix of train frequency and inverse time distance.

$$w_{ij} = \begin{cases} 0, & t_{ij} > t_t \\ freq/t_{ij}, & t_{ij} < t_t \end{cases} \quad (3)$$

t_{ij} is the traveling time between city i and city j, and t_t is the time threshold. Freq is the train frequency between the two cities.

This paper uses the panel data of 271 cities in China from 2010 to 2019 as the research sample. All data were obtained from the China Regional Economic Statistical Yearbook, the China City Statistical Yearbook, and the corresponding provincial and prefecture-level city statistical yearbooks and statistical bulletins. Table 1 shows the descriptive statistics of the panel data.

Table 1. Descriptive statistics.

Variable	Unit	Mean	Std.Dev	Min	Max
GDP per capita	Yuan	50,535	2.459	5304	215,488
Urban agglomeration (1 h)		2.784	2.373	−2.0797	8.477
Capital investment	%	77.668	29.094	12.449	229.61
Human capital	Person	187.566	241.351	0	1310.745
Foreign direct investment	%	1.766	1.797	0.0002	21.032
Government intervention	%	19.05	9.392	4.388	148.516
City scale	10^4 person	458.946	340.758	37.58	3124.32
Patents granted	Pieces	5261	12,342	10	166,609
Road area	10^4 m^2	2033	2608	15.4	22,160

4. Empirical Results

4.1. Benchmark Model

This paper is dedicated to investigating the impact of network externalities on urban growth. Firstly, we used Moran's I index to test whether the urban GDP per capita and the urban agglomeration index (1 h) fit the form of the spatial econometric model. The spatial matrix is a composite matrix of train frequency and inverse time distance under a 1 h time distance.

$$\text{Moran}'\text{s I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}, (i \neq j) \quad (4)$$

Table 2 shows the results of Moran's I index of GDP per capita and urban agglomeration IC. The results demonstrate that both variables have a significant spatial dependence. The results of the spatial effects test suggest that a spatial econometric model should be chosen. Based on the LR test, an individual and time dual fixed effects model should be selected. The Wald and LR spatial effects tests in Table 3 suggest that a spatial Durbin model should be used. For the follow-up results, the same tests of fixed effects, spatial effects, and spatial econometric model selection are conducted to ensure the robustness of the results.

Table 2. Moran's I test for GDP per capital and urban agglomeration.

Moran's I	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Pergdp	0.409 ***	0.358 ***	0.333 ***	0.321 ***	0.322 ***	0.383 ***	0.434 ***	0.496 ***	0.488 ***	0.509 ***
IC	0.531 ***	0.531 ***	0.531 ***	0.532 ***	0.531 ***	0.531 ***	0.532 ***	0.533 ***	0.534 ***	0.535 ***

Notes: *** represents the significance of 1%.

To further analyze the heterogeneity and robustness of network externalities at different spatial scales, we recalculated the urban agglomeration indicators IC at different time distances and kept the time distance of the IC index consistent with the urban network weight matrix.

Table 3. Results of network externalities on urban growth.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct effect	0.7618 *** (6.6682)	0.3793 *** (3.2454)	0.5786 *** (4.7966)	0.6063 *** (4.8457)	0.5334 *** (4.2619)	−0.0662 (−0.4085)
Indirect effect	0.2816 * (1.7273)	1.2233 *** (6.3745)	1.3026 *** (6.5038)	1.2533 *** (5.4402)	1.3514 *** (5.1268)	2.2084 *** (7.8123)
Total effect	1.0434 *** (5.2424)	1.6026 *** (7.2757)	1.8812 *** (8.7266)	1.8596 *** (7.6742)	1.8848 *** (7.1685)	2.1423 *** (7.9168)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
Wald spatial lag	123.35 ***	165.87 ***	166.39 ***	163.37 ***	148.53 ***	162.1 ***
LR spatial lag	50.6 ***	101.07 ***	94.89 ***	94.78 ***	93.89 ***	128.8 ***
Wald spatial error	190.69 ***	276 ***	317 ***	323.08 ***	315.79 **8	320.56 ***
LR spatial error	84.02 ***	193.32 ***	204.25 ***	220.78 ***	235.28 ***	301.14 ***
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct effect	−0.177 (−1.0496)	−0.1298 (−0.7209)	−0.5395 ** (−2.569)	−0.7029 *** (−3.742)	−0.7813 *** (−3.713)	
Indirect effect	2.4911 *** (8.4796)	2.5618 *** (8.2113)	3.0984 *** (8.657)	3.2865 *** (9.8659)	3.4069 *** (9.4772)	
Total effect	2.3141 *** (8.1009)	2.441 *** (8.2475)	2.5599 *** (8.1073)	2.5836 *** (8.3067)	2.6256 *** (8.1334)	
Controls	Yes	Yes	Yes	Yes	Yes	
Time effect	Yes	Yes	Yes	Yes	Yes	
Individual effect	Yes	Yes	Yes	Yes	Yes	
Wald spatial lag	174.8 ***	172.56 ***	173.37 ***	193.76 ***	180.51 ***	
LR spatial lag	136.4 ***	128.09 ***	141.47 ***	160.89 ***	167.29 ***	
Wald spatial error	325.39 ***	329.79 ***	312.12 ***	323.92 ***	303.92 ***	
LR spatial error	303.45 ***	303.08 ***	319.52 ***	337.05 ***	338.76 ***	

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

Table 3 presents the benchmark model results at different time distances. The direct effect of IC is positive and significant within 3 h and turns negative at 3.5 h of column (6). The significance also shows the transformation process from agglomeration economy to agglomeration diseconomy, and the effect on local growth gradually changes from positive promotion to effect weakening, and then turns to negative inhibition. The results demonstrate that there exists a critical point for the impact of increasing urban agglomeration on local economic growth. Along with the expansion of the considered time horizon, the agglomeration level of the city in the region is gradually increasing. However, as its carrying capacity is limited, it can only accommodate a certain scale of agglomeration level in the existing state. Therefore, with the expansion of the considered scope, the role of urban agglomeration on local growth shows a transformation process from agglomeration economy to agglomeration diseconomy. This is also a reflection of the characteristics of agglomeration externalities.

The indirect coefficients are significantly positive at every time distance, indicating that the agglomeration of urban economic activities has a significant spillover effect on other cities in the urban network, confirming the existence of network externalities and their positive impact on the growth of neighboring cities. The influence of the presence of other cities in the urban network and the interaction between cities on the economic growth of the target city cannot be ignored. This influence can prompt the target city to implement borrowed size and gain the agglomeration advantage shared in the urban network. In Figure 1, with the expansion of the time distance considered, that is, the expansion of the spatial scale of the urban network, the indirect coefficient generally presents an upward trend, from 0.2816 in 1 h to 3.4069 in 6 h. This indicates that the existence of network externalities and their positive effects on urban economic growth are unquestionable both in smaller regional networks and in relatively large cross-provincial networks. The continuously increased coefficients further indicate that the city in a larger network structure will be affected by stronger network externalities, which is different from the agglomeration externalities that decay with distance.

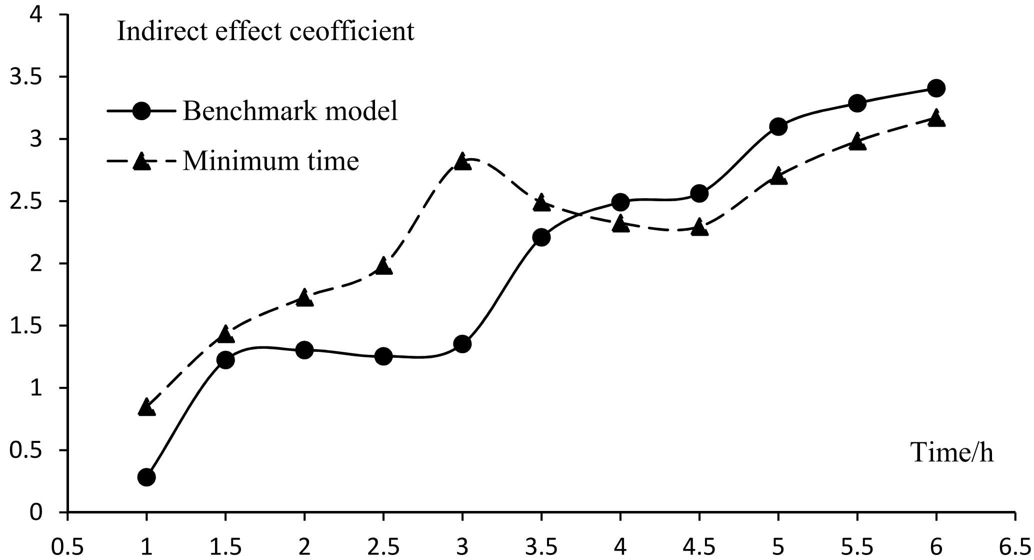

Figure 1. The indirect effect coefficients of benchmark model and robustness test.

4.2. Robustness Test

In the robustness test, the minimum time between the two cities is used to calculate the urban agglomeration index and the composite weight matrix.

Table 4 shows the regression results using the minimum time. The direct effect coefficient, indirect effect coefficient, and changing trend are all consistent with the results of the average time regression, which further confirms the robustness of the conclusion. In Figure 1, from the comparison between the shortest time and the average time, the indirect coefficients of the minimum time are higher within 3.5 h. The indirect coefficients calculated by the average time are higher beyond 4 h. The reason is that the shortening of travel time among cities promotes more cities to build functional connections and integrate into the urban network in a limited time. Not all cities integrated into the urban network can benefit from the network externalities with the expansion of the urban network. There may be some cities with competitive effects due to similar location characteristics, economic development stages, and future targets, thus offsetting some of the positive effects of network externalities.

The train frequency and inverse time distance matrix are also used separately to test the robustness of the results. The regression results are still stable and statistically positive; for brevity's sake, the result is not reported.

Table 4. Results of the minimum time.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.4071 ***	0.3699 ***	0.4335 ***	0.1355	−0.3969 **	−0.2508
effect	(3.5368)	(2.7913)	(3.446)	(0.8774)	(−2.3653)	(−1.5535)
Indirect	0.8489 ***	1.4339 ***	1.7279 ***	1.9839 ***	2.8223 ***	2.492 ***
effect	(4.1939)	(6.8889)	(7.463)	(7.3479)	(9.4813)	(7.6213)
Total	1.2559 ***	1.8038 ***	2.1615 ***	2.1194 ***	2.4254 ***	2.2411 ***
effect	(5.4049)	(7.919)	(9.0332)	(8.2807)	(8.8639)	(7.2385)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	−0.0698	0.0136	−0.3621 *	−0.4844 **	−0.5481 ***	
effect	(−0.3861)	(0.0701)	(−1.8832)	(−2.3185)	(−2.6098)	
Indirect	2.3239 ***	2.2957 ***	2.7055 ***	2.9826 ***	3.1718 ***	
effect	(6.8475)	(6.2397)	(7.148)	(7.2303)	(7.15)	
Total	2.2541 ***	2.3093 ***	2.3433 ***	2.4982 ***	2.6237 ***	
effect	(7.3195)	(7.0736)	(6.7311)	(6.4151)	(6.6205)	

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

4.3. Geographical Distance and Agglomeration Externalities

To examine the difference between agglomeration externalities and network externalities, in this section, urban agglomeration indicators are calculated by geographic distance, and agglomeration externalities and their trends with the spatial scale are investigated by using the inverse distance spatial matrix.

Table 5 shows the results of the urban agglomeration index and its spillover effects calculated from the agglomeration externality perspective using geographical distance. The spillover effects calculated using geographic distance are distinctly different from network externalities. In Figure 2, the indirect coefficients of IC calculated using geographic distance display an inverted U-shaped curve as the geographical distance increases, and the spillovers reach the maximum at 350 km and then decrease rapidly. The coefficients are no longer significant at 450 km and become negative at 500 km. The agglomeration spillover effect based on geographical distance is limited to a specific regional scope, and the externalities drop significantly beyond this distance threshold. In contrast, the network externality based on urban linkage does not show a decreasing trend with the expansion of temporal distance. It exhibits a significant increasing trend and the straight-line distance between the two cities is much smaller than the railway distance. It further confirms that network externalities do not arise based on geographical proximity, but rather generate spillover effects across regions through urban linkages. Moreover, network externalities have a more powerful impact on urban economic performance at a large-scale spatial level.

Unlike the scale perspective, the industrial specialization and diversification indices are used to investigate the impact of agglomeration externalities on urban growth from the perspective of industrial agglomeration. The industrial specialization index is calculated by the location quotient.

$$L_{ij} = \frac{e_{ij}/e_i}{e_j/e}, \ \mathrm{spec} = \max(L_{ij}) \tag{5}$$

L_{ij} is the location quotient, e_{ij} denotes the number of employees in the j-th industry of the i-th city, e_i denotes the total number of employees in city i, e_j denotes the number of employees in the j-th industry in the whole region. The maximum value of the location quotient of the city is the industrial specialization index.

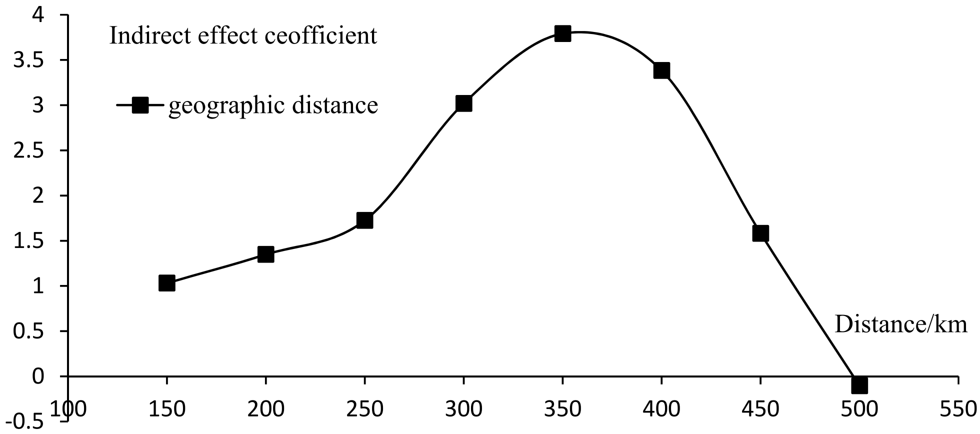

Figure 2. The indirect effect coefficients of using geographic distance.

Table 5. Results of using geographic distance.

IC	(1)	(2)	(3)	(4)
Geographic distance	150 km	200 km	250 km	300 km
Direct effect	0.4338 *** (2.7713)	0.4048 *** (2.3573)	0.1166 (0.6489)	−0.9891 *** (−3.0565)
Indirect effect	1.0313 *** (4.181)	1.3481 *** (3.8986)	1.7247 *** (4.213)	3.0194 *** (4.9362)
Total effect	1.465 *** (5.6873)	1.7529 *** (5.0105)	1.8413 *** (4.4665)	2.0303 *** (3.5473)
IC	**(5)**	**(6)**	**(7)**	**(8)**
Geographic distance	350 km	400 km	450 km	500 km
Direct effect	−1.3844 *** (−3.5048)	−1.1013 ** (−2.4851)	0.1726 (0.3248)	1.1688 ** (2.2357)
Indirect effect	3.7912 *** (4.582)	3.3831 *** (3.5501)	1.5822 (1.4334)	−0.1052 (−0.0818)
Total effect	2.4068 *** (3.1169)	2.2818 *** (2.6299)	1.7548 * (1.8349)	1.0636 (0.8826)

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

The industrial diversification is calculated by the The Herfindahl–Hirschman Index.

$$\mathrm{diver} = 1/\sum_{j}(\mathrm{e_{ij}}/\mathrm{e_i})^2 \quad (6)$$

Tables 6 and 7 provide the results of the direct and indirect effects from the industrial agglomeration perspective. The coefficients of IC in Tables 6 and 7 are similar to those in the benchmark model, proving the reliability and robustness of the conclusion. The direct effect coefficients of specialization are all significantly positive, indicating the existence of MAR externalities. The coefficients of diversity in Table 6 are all significantly negative, which indicates a negative influence on the local economy. The indirect effects of specialization and diversity are all not statistically significant. Agglomeration externalities measured by industry agglomeration data are limited to within the city. The reason may be that the network externalities are a macro-regional perspective, while industrial agglomeration is a micro perspective, and intercity industrial linkages need to be explored using more specific data. Compared to the results of agglomeration externalities measured from different perspectives, network externalities obviously have a larger spatial scope.

Table 6. Results of direct effects from industrial agglomeration perspective.

Direct Effect	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
IC	0.7824 ***	0.4069 ***	0.5925 ***	0.616 ***	0.538 ***	−0.0444
	(7.0159)	(3.3104)	(4.802)	(4.8857)	(4.2122)	(−0.2755)
Spec	0.0077 **	0.0102 ***	0.0095 ***	0.0103 ***	0.0106 ***	0.0103 ***
	(2.2683)	(3.1614)	(3.1309)	(3.1658)	(3.4978)	(3.4471)
Diver	−0.0084 ***	−0.007 ***	−0.0074 ***	−0.0077 ***	−0.0076 ***	−0.0068 ***
	(−3.2171)	(−2.6372)	(−2.9969)	(−3.1451)	(−2.1128)	(−2.6805)
Direct effect	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
IC	−0.1531	−0.1049	−0.5487 ***	−0.7005 ***	−0.7524 ***	
	(−0.9101)	(−0.6011)	(−2.7241)	(−3.6995)	(−3.5672)	
Spec	0.0102 ***	0.0108 ***	0.0127 ***	0.0127 ***	0.0126 ***	
	(3.2351)	(3.5267)	(4.1745)	(4.1171)	(4.1063)	
Diver	−0.0074 ***	−0.0077 ***	−0.0073 ***	−0.0068 ***	−0.0072 ***	
	(−3.0076)	(−3.3205)	(−2.9993)	(−2.8465)	(−2.8419)	

Notes: ***, ** represent significance of 1%, 5%, respectively.

Table 7. Results of indirect effects from industrial agglomeration perspective.

Indirect Effect	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
IC	0.3192 *	1.2248 ***	1.3714 ***	1.3195 ***	1.4067 ***	2.2122 ***
	(1.9374)	(6.3783)	(6.3791)	(5.8044)	(5.5532)	(7.9143)
Spec	−0.0029	−0.0061	−0.011 **	−0.0038	−0.0056	−0.0039
	(−0.4694)	(−1.1631)	(−2.0296)	(−0.6769)	(−0.9299)	(−0.5792)
Diver	−0.002	0.0054	−0.0005	−0.0024	−0.0021	−0.0025
	(−0.4615)	(1.2934)	(−0.1284)	(−0.5231)	(−0.4268)	(−0.4922)
Indirect effect	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
IC	2.524 ***	2.5773 ***	3.1584 ***	3.3405 ***	3.4158 ***	
	(8.6652)	(8.2572)	(9.0331)	(9.8964)	(9.6128)	
Spec	−0.0063	−0.0058	−0.0065	−0.0055	−0.0061	
	(−0.9451)	(−0.934)	(−0.8691)	(−0.7263)	(−0.7754)	
Diver	−0.0046	−0.0018	0.0021	0.0014	0.0009	
	(−0.8507)	(−0.3251)	(0.3504)	(0.2352)	(0.1383)	

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

4.4. Heterogeneity Analysis

To explore the regional heterogeneity of urban network externalities, we divide China into east and midwest regions according to geographical location. Tables 8 and 9 show the sub-regional results. The indirect effect coefficients in eastern China are all positive at the 1% significance level. In Figure 3, the indirect effects of the eastern region are all higher than the consequence for both the entire sample and the midwest region. Network externalities are found to be related to a well-developed railway infrastructure and an improved urban network structure that make the travel time among cities greatly reduced, leading to a profound impact on urban growth. Therefore, the network externalities are more significant in eastern China and their contribution to urban economic growth is stronger.

Table 8. Results of eastern region.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.5757 ***	0.2036	0.2694	0.1577	0.2964	−0.1632
effect	(3.3567)	(1.1007)	(1.4145)	(0.765)	(1.3581)	(−0.6997)
Indirect	1.2284 ***	2.0816 ***	2.22 ***	2.2541 ***	2.011 ***	2.571 ***
effect	(4.5805)	(7.3306)	(7.7265)	(6.8172)	(5.5924)	(7.5911)
Total	1.804 ***	2.2852 ***	2.4894 ***	2.4118 ***	2.3075 ***	2.4077 ***
effect	(5.9525)	(7.2591)	(7.6934)	(7.4955)	(6.9755)	(7.6414)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	−0.2754	−0.1902	−0.3972	−0.7757 ***	0.9479 ***	
effect	(−1.1849)	(−0.7998)	(−1.3692)	(−2.9826)	(−3.2841)	
Indirect	2.8886 ***	3.1539 ***	3.4167 ***	4.0058 ***	4.1889 ***	
effect	(7.6045)	(8.5549)	(7.9349)	(9.731)	(9.6999)	
Total	2.6132 ***	2.9636 ***	3.0195 ***	3.2301 ***	3.241 ***	
effect	(7.0554)	(8.6901)	(8.4502)	(9.3707)	(8.6651)	

Notes: *** represents the significance of 1%.

Table 9. Results of midwestern region.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.6903 ***	0.0674	0.6586 ***	0.5411 ***	0.469 ***	−0.2198
effect	(4.175)	(0.3765)	(3.9098)	(3.1315)	(2.7369)	(−0.9308)
Indirect	−0.2698	0.3873	−0.659 **	−0.6198 *	−0.2339	0.9471 **
effect	(−1.4872)	(1.5848)	(−2.1218)	(−1.7155)	(−0.5456)	(2.0502)
Total	0.4206 *	0.4546	−0.0004	−0.0787	0.2351	0.7273
effect	(1.6891)	(1.4491)	(−0.0011)	(−0.1919)	(0.5114)	(1.5364)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	−0.2211	−0.1029	−0.7506 ***	−0.6451 **	−0.6561 **	
effect	(−0.8951)	(−0.4011)	(−2.8381)	(−2.4236)	(−2.4475)	
Indirect	0.9731 *	1.027 *	2.3028 ***	2.0569 ***	1.981 ***	
effect	(1.8709)	(1.884)	(4.2368)	(4.2001)	(3.6182)	
Total	0.752	0.9242 *	1.5523 ***	1.4118 ***	1.3249 **	
effect	(1.4336)	(1.7601)	(2.9007)	(2.8195)	(2.4799)	

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

The indirect effect coefficients in the central and western regions are negative within 3 h. The coefficients turn positive at 3.5 h and are all significant at the 5% level. In Figure 3, the network externality increases first and then decreases slightly with the expansion of time, which reveals the limited network externality and the positive effect on urban growth at a larger spatial scale. Cities in the midwest regions are more scattered and the economy is relatively backward. The HSR network is not yet fully completed and cities with HSR are a few core cities. Most of the cities only have conventional railways with long travel times, so it is difficult to form effective urban connections under relatively small time distances. With the expansion of the time range, the gradual formation of urban linkages also produces network externalities to a certain extent, but the effect is insufficient.

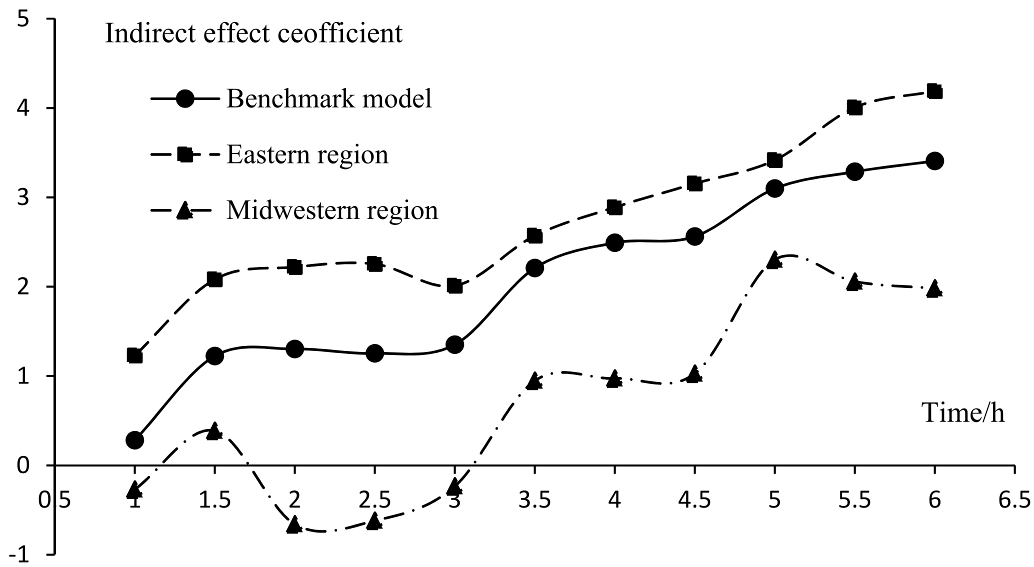

Figure 3. The indirect effect coefficients of different regions.

The above sub-regional differences suggest that there is significant heterogeneity in the growth effects of urban network externalities. The intensive intercity connection regions with advanced economies obtain more network externalities and have a more significant effect on driving urban economic growth.

4.5. Further Analysis

4.5.1. Accessibility and Connectivity Enhancement Effect

Compared to traditional railroads, the rise of HSR effectively compresses the spatial and temporal distances between cities, increasing urban accessibility and expanding the radiation range of cities. Only by accessing the high-speed rail network can cities enjoy the benefits associated with information connectivity, people mobility, and knowledge spillover from other cities. On the contrary, areas that are not yet connected to the HSR are at risk of being marginalized. Therefore, the construction of the HSR makes the agglomeration and radiation of cities occur in a wider geographical space and strengthens the intensity and depth of the urban network.

The empirical results in the previous sections are based on the data for all trains. To test whether improved traffic conditions strengthen the results of network externalities, we divided the train data into two categories and recalculated the IC and the urban network matrix. Specifically, the subsamples were distinguished into HSR trains starting with G, D, and C and general speed trains starting with K, T, Z, and numbers.

Table 10 shows the results of general speed railways. The results show that the direct effect coefficients are all positive at the 1% significance within 5 h. The coefficient is negative only at 5.5 h of column (10) and is no longer significant. When considering the railroad operation network of conventional trains, the travel time between cities is long, so the lower degree of urban agglomeration is at a relatively small spatial scope. The improvement of urban agglomeration intensity still exhibits a positive effect on local growth. The indirect effect coefficients change from negative to positive within 2 h with the increase in time. The coefficients are all positive at the 1% significance level at the time of 2.5 h and above. In Figure 4, the indirect effect displays an increasing trend with the expansion of time, which indicates the enhancement of network externality. Due to the slow speed of conventional trains, many cities cannot achieve effective interconnection within a relatively small-scale spatial level. Meanwhile, the emergence of agglomeration shadows and the competition effect among cities may make network externalities insignificant or even show negative effects. Under the traditional railroad network, cities can form interconnections and generate significant spillover effects only within a relatively efficient spatial scale.

Table 10. Results of conventional trains.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.4338 ***	0.5469 ***	0.6743 ***	0.3427 ***	0.4971 ***	0.2777 **
effect	(3.2431)	(4.2713)	(5.9825)	(2.6467)	(4.1441)	(2.0538)
Indirect	−0.5209 **	−0.2154	0.2106	0.7599 ***	1.0358 ***	1.3142 ***
effect	(−2.4984)	(−1.1356)	(1.2166)	(3.9219)	(4.9579)	(6.1535)
Total	−0.0871	0.3316	0.885 ***	1.1025 ***	1.5329 ***	1.5919 ***
effect	(−0.3105)	(1.3129)	(3.8649)	(5.1426)	(6.4764)	(6.6131)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	0.4805 ***	0.5723 ***	0.6847 ***	0.0773	0.144	
effect	(3.65)	(4.1022)	(4.4879)	(0.4298)	(0.7735)	
Indirect	1.1315 ***	1.1717 ***	1.1378 ***	1.7211 ***	1.7055 ***	
effect	(5.2482)	(4.8413)	(4.8458)	(6.138)	(5.8719)	
Total	1.612 ***	1.744 ***	1.8227 ***	1.7983 ***	1.8494 ***	
effect	(6.606)	(6.8879)	(7.4268)	(6.5308)	(6.5816)	

Notes: ***, ** represent significance of 1%, 5%, respectively. The number of cities is 252.

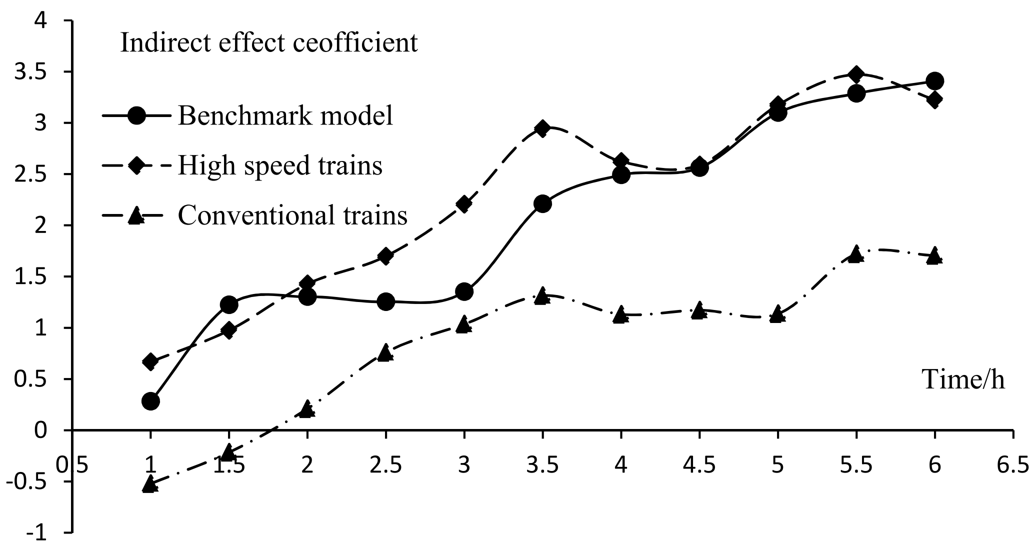

Figure 4. The indirect effect coefficients of different trains.

Table 11 presents the results of the HSR trains. The direct effect coefficients are consistent with the baseline model. At the same time scale, the presence of the HSR network enhances urban agglomeration, so its positive impact on local growth is significantly higher than that of both the baseline model and the general-speed trains. The coefficients are mostly insignificant when the direct effect turns negative at relatively large time scales. This demonstrates that despite the increase in agglomeration, the enhanced intercity interaction promotes the flow and optimal allocation of factors, which counteracts the agglomeration diseconomies generated by congestion. The indirect coefficients are all positive at the 1% significance, exhibiting strong network externalities. The coefficients increase from 0.6674 at 1 h to 3.2243 at 6 h, which indicates the same enhancement trend as the benchmark model.

Table 11. Results of HSR trains.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.8518 ***	0.7944 ***	0.936 ***	0.5925 ***	0.054	−0.3945
effect	(6.5107)	(5.5727)	(6.2824)	(3.6261)	(0.2451)	(−1.5756)
Indirect	0.6674 ***	0.9752 ***	1.4286 ***	1.6988 ***	2.2062 ***	2.9424 ***
effect	(3.6341)	(4.2656)	(5.3068)	(5.7228)	(6.3194)	(7.2399)
Total	1.5192 ***	1.7696 ***	2.3646 ***	2.2913 ***	2.2602 ***	2.5479 ***
effect	(6.7089)	(7.0124)	(8.5346)	(7.7253)	(7.1039)	(7.424)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	−0.1548	0.0003	−0.4542	−0.5493 *	−0.301	
effect	(−0.595)	(0.0013)	(−1.6055)	(−1.9528)	(−0.9973)	
Indirect	2.6219 ***	2.5883 ***	3.1752 ***	3.4713 ***	3.2243 ***	
effect	(5.9569)	(5.3117)	(6.3419)	(6.6894)	(5.934)	
Total	2.4671 ***	2.5887 ***	2.721 ***	2.9219 ***	2.9233 ***	
effect	(6.4682)	(6.2055)	(6.4503)	(6.5196)	(6.3801)	

Notes: ***, * represent significance of 1%, 10%, respectively. The number of cities is 231.

In Figure 4, from the comparison results of the sub-sample and the benchmark model, the indirect effect coefficients of high-speed trains are mostly higher than the results of the benchmark model. Due to the construction of the HSR network and the improvement of urban transportation conditions, the accessibility and connectivity of cities are greatly improved. Taking 1 h as an example, only 2928 datapoints are collected for general-speed trains, while 23,491 datapoints are collected for HSRs, and the average running time of HSRs is shorter. The construction of a HSR results in the integration of more cities into the urban network and a significant increase in accessibility. The high accessibility and low time cost further strengthen the agglomeration effect and accelerate the concentration of economic activities and the convergence of production factors. On the other hand, a significant rise in data volume is a significant increase in intercity flow volume, that is, an increase in connectivity in Social Network Analysis. The high interaction frequency accelerates the factor flows and leads to better sharing of agglomeration advantages among cities through the HSR network. Both effects reinforce the positive impact of network externalities and generate more powerful spillovers. In addition, when the time threshold is crossed, the spatial scale and interaction frequency of the HSR networks in which cities are located tend to stabilize. Smaller cities in the periphery that are gradually integrated into the HSR network may have competitive effects with other smaller cities resulting in the loss of agglomeration spillovers.

4.5.2. Multiple Borrowing Effects

In earlier studies, borrowed size is limited to one-way borrowing by small cities from large cities. Camagni et al. (2017) [42] also show that small and medium-sized cities are more likely to benefit from high-ranking urban networks. To test whether high-ranking cities play an effective radiating role and whether low-ranking ones can benefit from various ranking urban networks, we investigate the network externality among different types of cities by distinguishing the core and peripheral cities. The distance matrix with city categories is set up as follows:

$$w_{ij} = 1/t_{ij},\ t < t_t,\ i \neq j \quad (7)$$

City i is the core city and city j is the peripheral city, and vice versa.

$$w_{ij} = 1/t_{ij},\ t < t_t,\ i \neq j \quad (8)$$

City i and j are both core cities or peripheral cities, which is contrary to matrix 7.

Tables 12 and 13 provide the results of considering city categories. The indirect effect coefficients are positive and significant, showing obvious network externalities, whether considering the cross-regional urban network centered on the core city or the low-level regional urban network between similar cities. In addition, the indirect effect coefficient in column 1 of Table 13 is significantly negative, demonstrating that an urban network of low rank within a small area exacerbates the internal competition effect and leads to the dominance of agglomeration shadows. In Figure 5, the indirect coefficients of the two groups generally show an upward trend with the expansion of time distance, indicating stronger network externalities on a larger-scale spatial level, which is consistent with the previous results. In terms of differences, the spillover effect of urban agglomeration is stronger in higher-ranking urban networks. The reason may be that it is easier to build interactions and functional linkages between cities of non-equal size due to developmental differences. The positive effects of agglomeration are partially offset by the competitive effects of similar characteristics in low-ranking urban networks of similar cities. However, it is worth acknowledging that small and medium-sized cities not only gain development momentum from the spillover effects of core cities but also generate mutual borrowed size among similar cities, showing the characteristics of network externalities.

Table 12. Results of interaction with different cities.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct	0.8733 ***	0.6616 ***	0.7073 ***	0.5688 ***	0.6422 ***	0.5349 ***
effect	(8.7054)	(6.3816)	(6.5825)	(5.2408)	(5.3243)	(3.9689)
Indirect	0.6066 **	1.3254 ***	1.5119 ***	1.7334 ***	1.1291 ***	1.733 ***
effect	(2.2434)	(6.1971)	(6.3966)	(6.2332)	(3.9304)	(5.8931)
Total	1.4799 ***	1.987 ***	2.2193 ***	2.3022 ***	1.7713 ***	2.2679 ***
effect	(4.9569)	(8.3848)	(8.5393)	(7.9499)	(5.8496)	(7.5345)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct	0.4217 ***	0.5277 ***	0.4217 ***	0.3767 **	0.2705	
effect	(3.1621)	(3.7318)	(2.6278)	(2.3561)	(1.5911)	
Indirect	2.4054 ***	2.4255 ***	2.5988 ***	2.6047 ***	2.7498 ***	
effect	(8.2753)	(7.6333)	(7.8967)	(8.3647)	(7.9545)	
Total	2.8272 ***	2.9532 ***	3.0204 ***	2.9814 ***	3.0203 ***	
effect	(9.7042)	(9.3624)	(9.076)	(9.3926)	(8.8687)	

Notes: ***, ** represent significance of 1%, 5%, respectively.

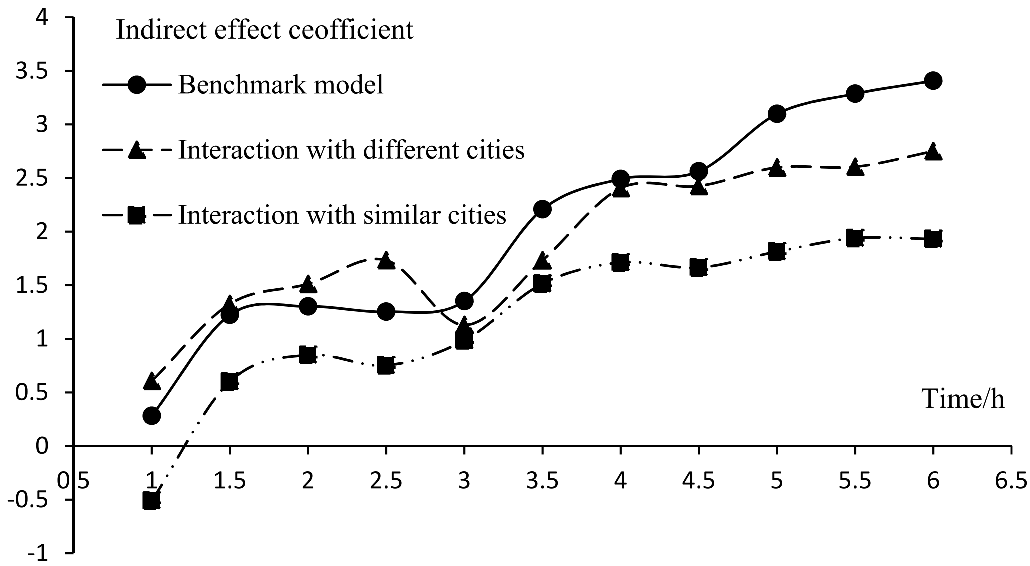

Figure 5. The indirect effect coefficients of city categories.

Table 13. Results of interaction with similar cities.

IC	(1)	(2)	(3)	(4)	(5)	(6)
Time	1 h	1.5 h	2 h	2.5 h	3 h	3.5 h
Direct effect	0.8364 *** (8.2833)	0.4816 *** (4.2442)	0.5632 *** (5.1035)	0.6394 *** (5.4436)	0.5565 *** (4.7309)	0.3376 *** (2.5998)
Indirect effect	−0.5098 *** (−3.3475)	0.6009 *** (3.4313)	0.85 *** (4.5127)	0.7529 *** (3.8604)	0.9856 *** (4.5728)	1.5152 *** (6.8794)
Total effect	0.3265 * (1.8035)	1.0825 *** (5.3955)	1.4133 *** (7.1185)	1.3923 *** (7.0752)	1.5421 *** (7.0822)	1.8527 *** (8.5101)
IC	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	
Time	4 h	4.5 h	5 h	5.5 h	6 h	
Direct effect	0.2789 ** (2.0581)	0.2856 * (1.9283)	0.2257 (1.395)	0.1296 (0.81)	0.1431 (0.815)	
Indirect effect	1.7122 *** (7.7551)	1.665 *** (6.8895)	1.8143 *** (6.9836)	1.9395 *** (7.5926)	1.9322 *** (7.107)	
Total effect	1.991 *** (9.2179)	1.9506 *** (8.4645)	2.0399 *** (8.455)	2.0691 *** (8.6442)	2.0753 *** (7.872)	

Notes: ***, **, and * represent significance of 1%, 5%, and 10%, respectively.

5. Conclusions and Recommendations

5.1. Main Conclusions

This paper uses the train frequency and the travel time data of 271 cities in China to construct the urban network matrix of urban networks to investigate the impact of urban agglomeration on urban economic growth from the perspective of network externality by the spatial econometric model. The main findings are as follows.

There are significant network externalities among Chinese cities that play an important role in driving urban growth. Whether in a relatively small neighboring regional urban network or in a large urban network at the national level, urban network externalities contribute to urban growth. Furthermore, the positive effect increases with the expansion of the network scope. The results of urban agglomeration indicators based on geographic distance and the industrial agglomeration perspective indicate that agglomeration externalities are spatially limited. Network externalities are no longer predicated on geographic proximity. Non-adjacent cities can also share agglomeration advantages through intercity interactions and generate cross-regional spillover effects based on urban networks. The network externality likewise exhibits spatial scale disparity and regional heterogeneity. In other words, cities can obtain borrowed size from multiple urban networks of different scopes, namely, spillover effects from core cities and mutual borrowing among similar cities, respectively. The construction of the HSR network further enhances the accessibility and connectivity of cities, promoting agglomeration while mitigating the congestion effect of cities themselves. It also reinforces the benefits of network externalities on urban growth by enhancing urban interactions.

5.2. Policy Recommendations

In the process of urban development, shifting from the agglomeration advantage of a single city in an administrative district to focusing on the synergistic advantage of networked urban development is the top priority in building the future urban network system, giving full play to the positive role of urban agglomeration and avoiding the negative effects caused by over-agglomeration as well as the competitive effects and agglomeration shadows produced by homogeneous development. Based on regional development stages and characteristics, the scale of regional development policies can be refined and differentiated and targeted regional development strategies implemented. The promotion of the construction of transportation infrastructure will accelerate the interconnection of cities, further improving urban accessibility, and creating favorable conditions for borrowed size and network externality. Accelerating the layout of the high-speed rail network will shorten the city's space-time distance, especially the construction of the intercity railway between the core cities and the surrounding hinterland cities as well as the transportation constraints in remote areas. Making the central cities bigger and stronger is an important source for small and medium-sized cities to implement borrowed size. The expansion and extension of the channels and ways of urban connection will help small and medium-sized cities with low agglomeration levels to embed in different levels of urban networks, and build the development situation of small and medium-sized cities borrowing from each other.

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