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Research Article

Spatial Pattern of Urban System Based on Gravity Model and Whole Network Analysis in Eight Urban Agglomerations of China

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An urban agglomeration (shorted as UA) is a highly developed spatial form of integrated city and an important driving force for regional economic development. The network of UA mainly reflects the spatial connections and organizational structure of all cities, which is of great significance for understanding the development status of UAs and revealing their development laws. However, there are few horizontal studies comparing the network structure of China's UAs. This study constructs the economic network of China's eight UAs with the gravity model and explores the overall network structure and city centrality using indicators in network analysis. Then, two groups of UAs with similar network structures are compared. Finally, the association between the gravity model and empirical data is discussed. The results show that the spatial pattern of cities in UAs can be expressed by the gravity model approximately. Besides, UAs with different development levels present different spatial network structures, but the network structures cannot reflect the development levels of UAs directly. We also find that the cities with high betweenness centrality have greater development potential to be the next growth pole.

1. Introduction

Urban agglomeration (shorted as UA) refers to the development of a large or megacity in a specific area, with at least three metropolitan megalopolis, or large cities, as the basic unit. Infrastructure networks, such as transportation and communication, help in forming an urbanized and highly integrated urban group with close economic connections [1]. An advantage of UAs over single cities is their improved ability to accelerate resource flows, strengthen industrial cooperation, and break administrative restrictions. UA will be an important driving force for economic development in the future [2]. Affected by geographical location, natural resources, and development policies, the interconnected structure and spatial organization of UAs are quite unique, resulting in their different development levels. Therefore, in order to clarify the direction of urbanization construction and promote the development of underdeveloped regions, it is necessary to study the spatial connection and organizational structure of each existing UA.

The traditional study of urban hierarchy usually relies on central place theory, emphasizing the city's leading position and substitution, while ignoring mutual help and cooperation between cities [3]. The concept of the "city network" has broken down the limitations of traditional theory, providing another way of understanding the division of labor between cities [3–5]. It has been concluded that the network model is more suitable than central place theory to illustrate the cooperation relationship between cities [6]. Under the process of globalization, economic activities are becoming more frequent worldwide, creating a new economic and social landscape in the global space [7]. In the study of the world city network, much research has been carried out on three important aspects: transportation networks [8–12], social and cultural networks [13–15], and business cooperation networks [9, 16, 17]. These studies have deepened our understanding of the interrelationships between cities and provide a reference for studying UA networks in smaller regions.

UA network research is an important part of understanding a city network. It mainly concerns the division of labor between cities in a specific region [18]. The UA network concept has attracted much attention due to its complexity. Compared with the world city network, the UA network has a smaller scope, but it also has a varying network structure. Different network structures mean different development states and levels. A considerable amount of research has been conducted on UA networks [19–23]. For instance, Burger et al. used commuter data to study the England and Wales city region and found that most UAs are increasingly polycentric, but there are also some UAs that are becoming more monocentric [19]. Hall et al. studied eight UAs in Europe and revealed their internal urban-organization structure [20]. Vasanen measured the multicenter characteristics of three Finnish UAs through commuter data [21].

Driven by the research above, China, as the largest developing country, has attracted extensive attention to the spatial organization structure of its UAs [24–31]. Zhao et al. used the cooperation data of companies to analyze the internal structure of China's two major UAs [24]. Sun compared structural differences in roads, railways, and social networks in the Yangtze River Delta [26]. Han and Zhang analyzed the spatial organization structure of the Yangtze River Delta [27, 28]. Fan et al. studied the city network structure of the Huaihe River UA [29]. As a country with an active economy, China's urbanization has received extensive attention around the world [32]. For the study of China's UA networks, the existing literature mainly concentrates on urban areas with a high level of development, but general horizontal comparative analysis is lacking [17, 26, 28]. In fact, due to differences in geographical location, natural conditions, and policies, the development processes of various UAs in China vary dramatically and have different spatial structures [17, 33]. Horizontal comparative studies would help us to better understand the network structure of China's UAs and provide reference for urbanization in underdeveloped regions.

The gravity model is a theoretical model that can transform attribute characteristics into relationships and reflect the possible total connection between cities [34]. Most of the existing researches reveal the interrelationships between cities based on a specific dimension, such as commuter networks, railway networks, or social networks, which can only reflect a certain aspect of potential interaction between cities [35, 36]. This potential connection is always transformed into empirical connections by a certain ratio [37]. Therefore, the potential interaction is of great significance in understanding the spatial structure in UA and would provide an important basis for its development and planning [38, 39]. On the contrary, when comparing the network structure of different UAs, there exist some difficulties in using actual transport data and enterprise cooperation data. For example, due to administrative divisions, the statistical specifications of different regions vary, so the data are not recorded in the same order of magnitude. However, the size and unit of each city's data and their spatial distance are the same, and this is the ideal data for comparing differences in UAs. Therefore, considering data availability, it is more realistic to introduce the gravity model to study the network structure of UAs.

As a basic concept of network analysis, centrality was first proposed by Freeman and was applied to the study of urban systems by Irwin, mainly reflecting the relative importance of external city services [40, 41]. In a city network, the central city is a hub that promotes the efficient flow of various elements [42]. In order to understand the spatial organization structure of UAs in urban system planning and city-function analysis, the city hierarchy can be divided according to the centrality of a city [43].

In view of this, this study constructs the network of China's eight UAs through the gravity model and compares their spatial structure with network analysis indicators such as density and average path length. Then, we analyze the centrality of different cities. The development status of each UA is revealed. The innovations of this study include (1) introducing the gravity model to construct the city network of a UA, (2) comparing the network structure and centrality of the eight major UAs in China, and (3) demonstrating that degree centrality has a high degree of correlation with betweenness centrality in UA networks, and betweenness centrality gradually transfers from the central city to peripheral cities during UA development. In addition, a UA with a multicenter, evenly distributed network structure does not necessarily represent a highly developed status.

The rest of the paper is organized as follows: Section 2 explains the analytical framework. In Section 3, we discuss the results and further compare two groups of UAs with a similar network structure. In Section 4, the spatial structure of city network obtained by the gravity model and empirical flow are compared and some policy implications are discussed. The final section concludes the study and offers an overview of future research issues.

2. Methods and Data

Based on the existing research described above, this study intended to construct the UA network with the gravity model and analyzed UA networks through network science indicators. This section focuses on the construction methods, analytical indicators, and data sources of UA networks.

2.1. Construction of the City Network. The gravity model originated from physics and was used to describe the interaction between two objects:

$$F = G\frac{M_1 M_2}{d^2}, \tag{1}$$

where M_1 and M_2 indicate the masses of two objects, d is the distance between the two objects, and G is the universal gravitation constant. Similar to the interaction between objects, there is also interaction between cities in a certain area. Based on the universal gravity model, Zipf proposed the gravity theory to describe the interrelationships between cities [34]. He assumes that the connection between cities depends on the scale of the two cities and their spatial distance and that the strength of the connection is proportional to the city scale and inversely proportional to the spatial distance. The theory implies that the economic phenomena of cities are concentrated at the economic or administration center; the economic activities of the cities are similar, and the connection between cities is mutual. The basic formula is as follows:

$$F = \frac{M_i M_j}{d^{\alpha}}. \tag{2}$$

In earlier studies, M usually represents the population scale, d indicates the Euclidean distance, α is the distance attenuation coefficient, and F represents the potential intensity of population movement between the two cities. In later studies, scholars consider that the intensity of interaction is determined not only by the population scale but also by the comprehensive strength of the city. Therefore, different scholars have separately set M according to the content of their own research.

In the process of rapid urbanization, economic activity is a core property in urban interactive influence, but the development of economic activity must be supported by favorable society conditions. Economic and social factors are integrated in the process of urban development [39]. Thus, these two factors are mainly considered in this study. The GDP scale is selected to represent the economic activities, and the population scale represents social conditions. Because the selection of indicators cannot fully represent all aspects of urban connections, such as cultural connections, and in order to highlight economic linkages between cities, the UA network structure considered in this study refers to macroeconomic city networks.

In addition, the spatial distance between cities is a barrier to urban economic connections. However, the Euclidean distance cannot reflect the obstacles of the connection precisely. In reality, spatial distance is usually expressed by the travel distance between cities. It is obvious that the more developed the transport infrastructure is, the smaller the effect of the spatial distance between cities will be. Compared with aviation, railway, and water transportation, highway is more common in the UA region. Thus, in this study, the highway distance between cities is used.

α reflects the rate of increase of the friction of distance. Affected by different flows, its value usually varies between 1 and 3 (Table 1). Since this study uses highway distance to represent the resistance of the relationship between cities, we set $\alpha = 2$ according to reference [44].

Therefore, this study defines the economic relationship g_{ij} between cities i and j as

$$g_{ij} = \frac{\sqrt{p_i \times v_i} \times \sqrt{p_j \times v_j}}{d_{ij}^2}, \tag{3}$$

where p represents the population of the city, v represents the gross domestic product (GDP) of the city, and d_{ij} is the highway distance between cities i and j.

Table 1: The coefficient of different flows.

Type	Study area	α
Subway [45]	Seoul metropolitan	2.68
Korean highway [44]	Korea	2
Influenza [46]	$d < 119$ km	3.05
Telephone communication [47]	Belgian	2
Railway express [34]	13 cities	1
Train flows	England and Wales city	1.44
Bus flows [48]	clusters	1.91

Based on the above description, assuming a UA contains N cities, the connections between them are an $N \times N$ symmetrical matrix and can be represented by network G. It should be noted that the city's GDP value v and population scale p would not usually be zero, so g_{ij} is always greater than zero. That means that a UA network constructed with the gravity model is a fully connected network. In order to reveal different characteristics of UAs, we need to compare different network structures. However, through these completed networks, it is difficult for us to compare and analyze their structural indicators. Considering this situation, this study proposes a method of generating UA networks based on the gravity model. The method framework is shown in Algorithm 1.

The purpose of this method is to delete minimum weights in the completed network. However, considering the development level of different UAs, this method does not delete minimum-weight edges in the entire network but deletes the k_i edge with the minimum weight in each city i and keeps the network connected. The design principles of this method are (1) keeping the network connected, (2) ensuring deleted edges have a minimal contribution to each city, and (3) ensuring that different UAs delete edges according to their own development status. As shown in Figure 1, X is an urban agglomeration with a higher weight and Y is the one with a lower weight. Although they have similar local network structures, their development status is quite different. Our method can ensure that not too many edges in Y will be deleted and not too many will be retained in X for a higher weight. According to their own weight, e (2, 3) in X and e (1, 2) in Y are deleted.

2.2. Analytical Framework. Based on the UA networks, this study mainly analyzes their structure from three aspects.

2.2.1. Overall Network Structure. The indicators of overall network structure include network density, average path length (APL), and average clustering coefficient (ACC). Specifically, network density can be expressed as

$$D = \frac{m}{n(n-1)}, \tag{4}$$

where m is the number of edges and n is the number of nodes in the network. Density is the ratio of the actual number of edges to the possible number of edges in the network. For the UA networks in this study, the actual number of edges m

Input: $G = (V, E, w)$, the completed network with weight;
Output: G reconstructed network
while G is connected **do**
  for each node i **in** G
    w_{ij} is the smallest weight among the edges of nodes i
    remove the edge e (i, j) from G
  end for
  end while
return G

Algorithm 1

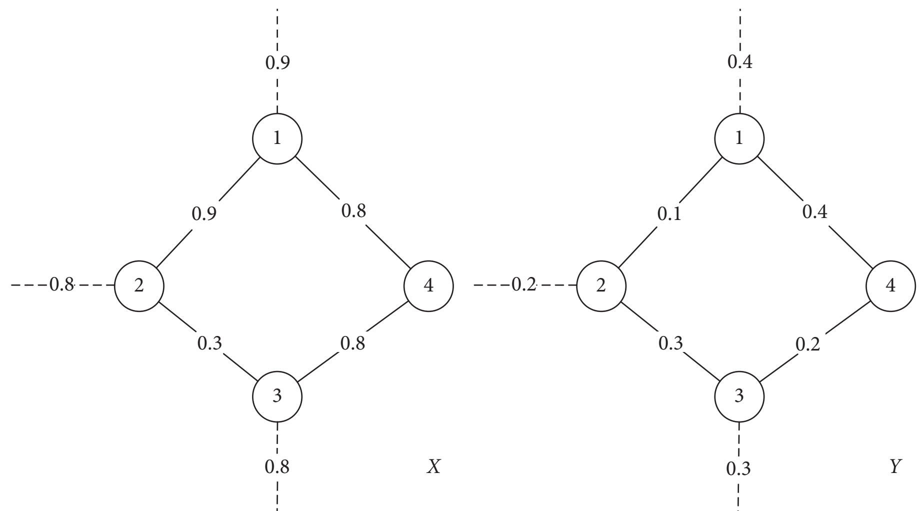


Figure 1: Schematic view of the proposed edge-deletion method.

represents the connection that must be kept to maintain network connectivity, which reflects effective economic connections between cities. Thus, the higher the density is, the more integrated the economic connections are.

For undirected networks, APL can be expressed as

$$L = \frac{2}{n(n-1)} \sum_{i \neq j} d_{ij}, \quad (5)$$

where d_{ij} represents the shortest distance between any two nodes. For a UA network, the shortest distance between cities indicates the minimum number of geodesic lines that the city needs to be connected; that is, the length of an economic connection path between cities. Obviously, the shorter the path length is, the more direct the economic connection is.

The ACC of an undirected network is the average of the clustering coefficients of all nodes in the network. For node i of degree k_i, its clustering coefficient C_i is defined as

$$C_i = \frac{1}{k_i(k_i - 1)} \sum_{j,k}^{N} a_{ij} a_{jk} a_{ki}, \quad (6)$$

where $\sum_{j,k}^{N} a_{ij} a_{jk} a_{ki}$ indicates the number of triplets in the network that contains node i. The clustering coefficient of node i can be interpreted as the ratio of the number of closed triplets to the number of all triplets. A high clustering coefficient indicates that the nodes tend to cluster together. For UA networks in this study, the higher the ACC is, the higher the local clustering degree of the city and the closer the economic relationship. Otherwise, city development is relatively independent.

2.2.2. City Centrality. Node centrality measures the importance of nodes in the network. This study mainly focuses on degree centrality (DC) and betweenness centrality (BC). Specifically, DC is generally used to describe the ability of a node to occupy resources. According to Freeman [49], the DC of a node i can be expressed as

$$C_d^i = \sum_{j=1}^{n} d_{ij}, \quad (7)$$

where d_{ij} indicates the edge weight between node i and node j. For UA networks, the higher the degree centrality of a city is, the more likely it is to be the center of the network.

The BC of a node is often used to describe the ability of a node to control resources in a network. According to Freeman, BC is defined as

$$C_b^i = \sum_{j<k} \frac{g_{jk(i)}}{g_{jk}}, \tag{8}$$

where $g_{jk(i)}$ quantifies the times that node i is an intermediary node along the shortest path between nodes k and j and g_{jk} quantifies the sum of all of the shortest paths between nodes k and j. The weighted BC reflects the proportion of the weight passing through node i to the total weight of the network. The higher the ratio is, the stronger the ability of node i to control the flow of resources among other cities is. For UA networks, the BC of a city indicates the ability of a city to control the economic connections of other cities, which is a main indicator for measuring the importance of cities in a UA network.

2.2.3. Network Centralization. Based on node centrality, this study further introduces network centralization to analyze the overall concentration of the network. The general form of network centralization can be expressed as

$$C_g^* = \frac{\sum_i [\max(C_*) - C_*^i]}{\max \sum_i [C_* - C_*^i]}, \tag{9}$$

where C_* is a general representation of network centrality. Network centralization measures the difference in centrality between the network center node and other nodes. The network centralization of a star network equals 1, indicating there is only one center. If network centralization is 0, the network is ring shaped, and the nodes in the network are of the same importance. For weighted networks, considering the impact of weight on centralization, when calculating $\max \sum_i [C_* - C_*^i]$, this study assigns the maximum weight in the actual network to the edge of a star network containing the same number of nodes. For UA networks, centralization reflects the concentration trend of cities. If network centralization is large, UA development tends to concentrate in one or several centers. On the contrary, if network centralization is small, the UA network tends to be more polycentric.

2.3. Study Area and Data Sources. This study selected eight national UAs covering almost all regions in mainland China, which is helpful to understand China's overall UA development status. Their geographical distribution is shown in Figure 2.

Among the eight UA networks, Beijing-Tianjin-Hebei (shorted as BTH), Yangtze River Delta (shorted as YRD), and Pearl River Delta (shorted as PRD) are the three most famous urban agglomerations in China, and they are also the most developed regions. BTH is the political center of China. YRD and the PRD are adjacent to the ocean. They occupy convenient geographical conditions for economic development. Ha-Chang (HC) is located in China's northeast and is one of the important old industrial bases. However, in the process of economic development, its development rate has not been as fast as those of the southeast coastal areas. The Zhongyuan (ZY) UA is located in central China, occupying a very important transportation location. The Guanzhong (GZ) UA is located in the northwest. It has poor transportation conditions and a weak economic foundation. Both the Cheng-Yu (CY) and the Mid-Yangtze (MY) UAs are located in the Yangtze River economic belt. The CY UA is farther from the sea, so its development speed is not as fast as that of MY. The economic development level of each selected UA is different, representing the various stages of UA development, and this is meaningful for comparison analysis.

Table 2 shows the cities contained in each UA (determined according to the national plan of each UA). Statistical data used in this study mainly come from the "2017 China Urban Statistical Yearbook" [50] and the "2016 National Statistical Report on National Economic and Social Development" [51]. Spatial data come from Baidu Maps (updated in June 2018) [52].

3. Results

3.1. Spatial Distribution. Based on the data sources mentioned in Section 2, we used the proposed method to construct the economic network of eight UAs in China. The analyzing environment for building the networks and for the indicator calculation was Python 3.6. The spatial distribution of the economic network of the eight UAs is shown in Figure 3.

In general, the network structure of the eight UAs is spatially distributed around cities with a higher economic development level and gradually radiates outward. The farther away from the central city, the fewer edges and weights there are. Specifically, the BTH UA forms an economic concentration zone dominated by Beijing, Tianjin, and Shijiazhuang. PRD is mainly concentrated around Guangzhou and Foshan. Affected by the convenience of inland waterway transportation conditions, YRD's economic network is mainly concentrated along the Yangtze River. In MY, Wuhan and Changsha are the capital cities of the Hubei and Hunan province, respectively. The network structure mainly radiates to other cities from these two cities and is distributed around the Yangtze River. Similarly, CY has a network centered on Chengdu and Chongqing. The surrounding cities are mainly connected through these two important nodes. The ZY UA network is star shaped, with strong economic links between major cities and weak economic links between peripheral cities. The HC UA network is relatively sparse and has fewer connections. Due to geographical restrictions, the GZ UA network is strip shaped. The large distance between east and west is an important factor limiting the development of this UA.

3.2. Topological Structure. Based on the study of spatial structures and using the indicators mentioned in Section 2, we describe the basic topology properties of UA networks in this section. Basic structural properties are shown in Table 3.

As shown in Table 3, the UA with the most network nodes and edges is MY. PRD has the largest average

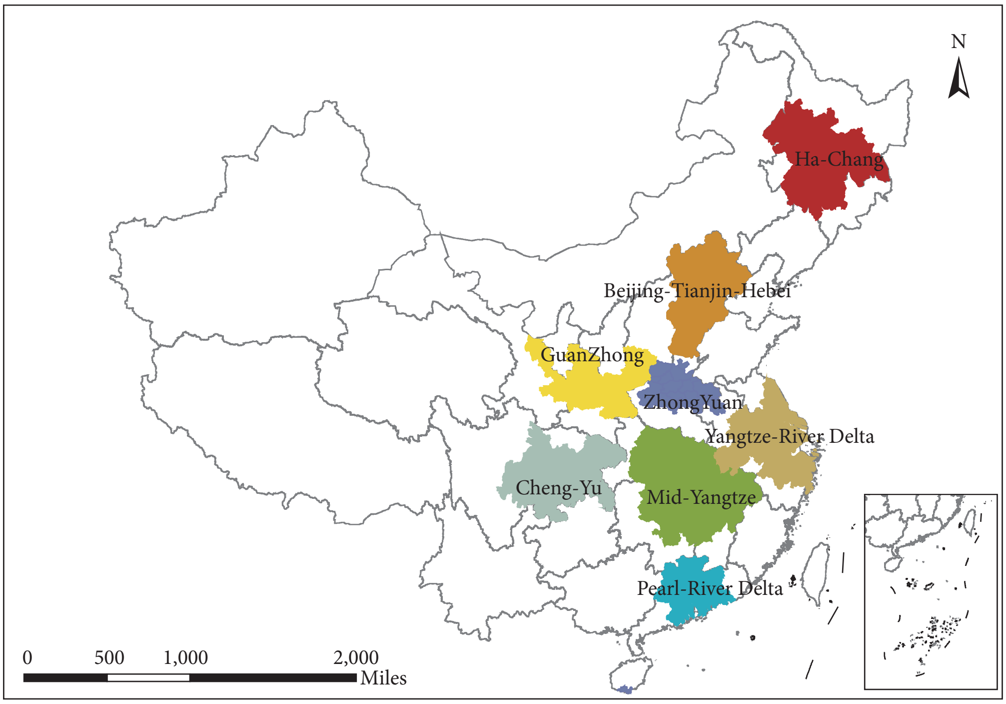


Figure 2: Location of eight urban agglomerations in China.

Table 2: Cities in each urban agglomeration.

Urban agglomeration	City
Ha-Chang	Harbin, Daqing, Qiqihar, Suihua, Mudanjiang, Changchun, Jilin, Liaoyuan, Songyuan
Beijing-Tianjin-Hebei	Beijing, Tianjin, Baoding, Tangshan, Shijiazhuang, Langfang, Qinhangdao, Zhangjiakou, Chengde, Cangzhou, Hengshui, Xingtai, Handan
Yangtze River Delta	Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, Taizhou, Hangzhou, Ningbo Jiaxing, Huzhou, Shaoxing, Jinhua, Zhoushan,Hefei, Wuhu, Maanshan, Tongling, Anqing, Chuzhou, Chizhou, Xuancheng
Pearl River Delta	Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Huizhou, Zhongshan, Jiangmen, Zhaoqing, Shanwei, Qingyuan, Yunfu, Heyuan, Shaoguan
Zhongyuan	Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Xinxiang, Jiaozuo, Xuchang, Luohe, Jiyuan, Hebi, Shangqiu, Zhoukou, Jincheng, Bozhou
Guanzhong	Xi'an, Xianyang, Baoji, Weinan, Tongchuan, Shnagluo, Yianshui, Pingliang, Qingyang, Linfen, Yuncheng
Cheng-Yu	Chongqing, Chengdu, Zigong, Luzhou, Deyang, Mianyang, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin, Guangan, Dazhou, Ya'an, Ziyang
Mid-Yangtze	Wuhan, Huangshi, Ezhou, Huanggan, Xiaogan, Xianning, Xiantao, Qianjiang, Tianmen, Xianyang, Yichang, Jingzhou, Jingmen, Changsha, Zhuzhou, Xiangtan, Yueyang, Yiyang, Changde, Hengyang, Loudi, Nanchang, Jijiang, Jindezhen, Yingtan, Xinyu, Yichu, Pingxiang, Shangrao, Fuzhou, Jian

degree (weighted), and HC has the smallest. By comparing the BTH, PRD, and ZY UAs, as well as the HC and GZ UAs, it can be found that these two groups have the same number of nodes, but the number of edges, the average degree, and other indicators are quite different, indicating that the proposed method can highlight differences in the economic network of UAs and reflect the development status of the UAs. In order to further compare the differences in network density, ACC, and APL among different UAs, this study describes their joint distribution in Figure 4, where the horizontal axis represents APL, the vertical axis represents ACC, and the size of the point denotes density.

According to Figure 4, the eight UAs can be divided into three categories: (1) UAs with lower APL and higher ACC, such as BTH and PRD. In general, a network with a small APL and large ACC is considered to have the characteristics of a small-world structure [53]. Therefore, these two UAs are more likely to have small-world features than other UAs. At the same time, the network density of these two cities is relatively large, indicating that the cities in these two UAs have close economic connections. Network structure is more likely to promote the exchange of economic resources between cities and promote their further development. (2) UAs with a medium APL and high ACC. This type of UA includes YRD, MY, CY, HC, and ZY. The network density of such

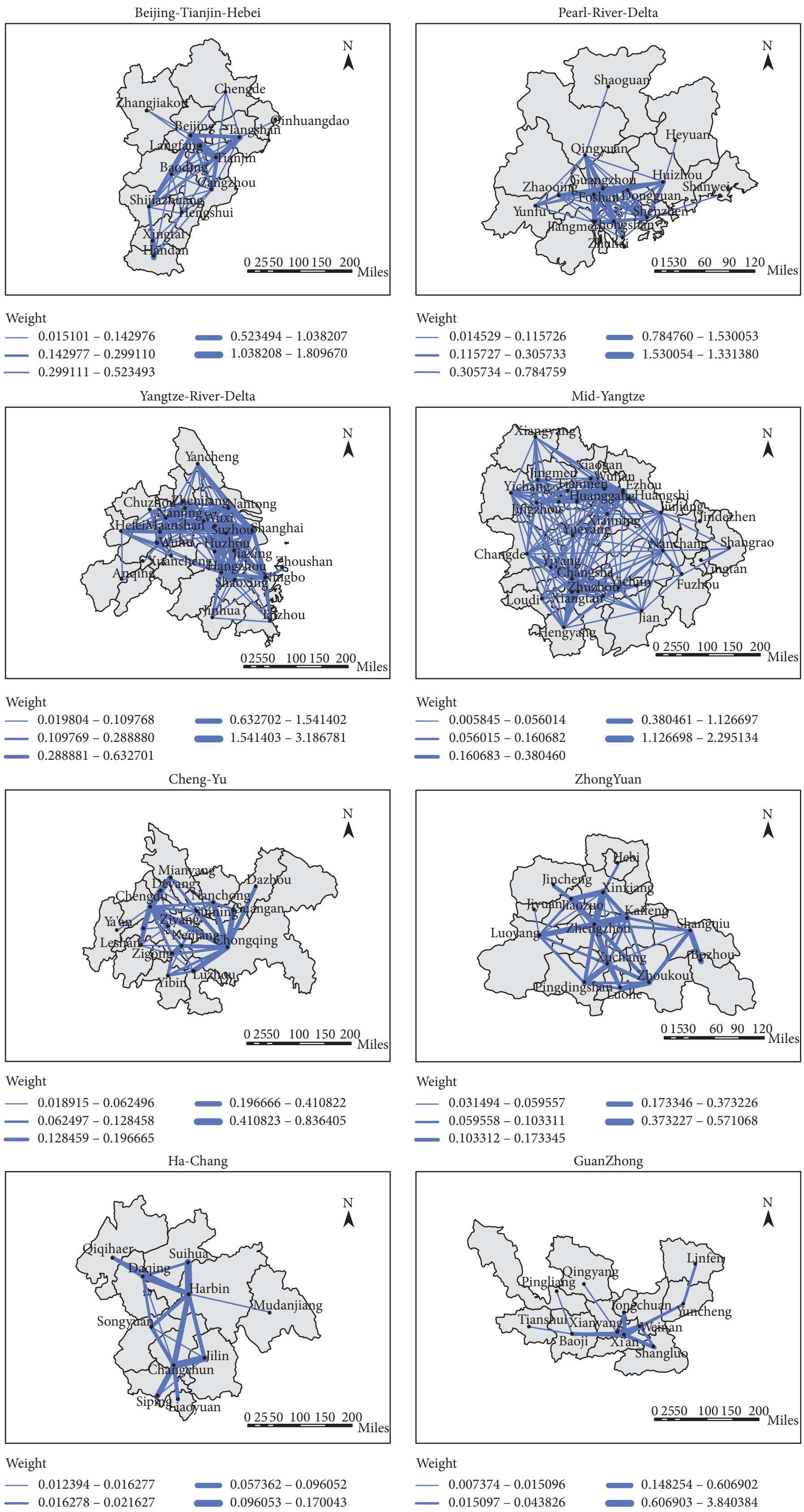


Figure 3: Economic connections in each urban agglomeration.

Table 3: Basic structural properties.

	Number of nodes	Number of edges	Average degree (weighted)	Density	Average clustering coefficient (ACC)	Average path length (APL)
BTH	13	40	1.642	0.513	0.736	1.577
PRD	14	50	3.368	0.549	0.672	1.527
YRD	25	127	2.475	0.423	0.672	1.803
MY	31	187	0.857	0.402	0.695	1.766
CY	16	43	0.746	0.358	0.624	1.775
ZY	14	37	0.765	0.407	0.517	1.846
HC	10	17	0.184	0.378	0.573	1.756
GZ	11	16	0.916	0.291	0.355	2.091

PRD, Pearl River Delta; YRD, Yangtze River Delta; MY, Mid-Yangtze; CY, Cheng-Yu; ZY, Zhongyuan; HC, Ha-Chang; GZ, Guanzhong.

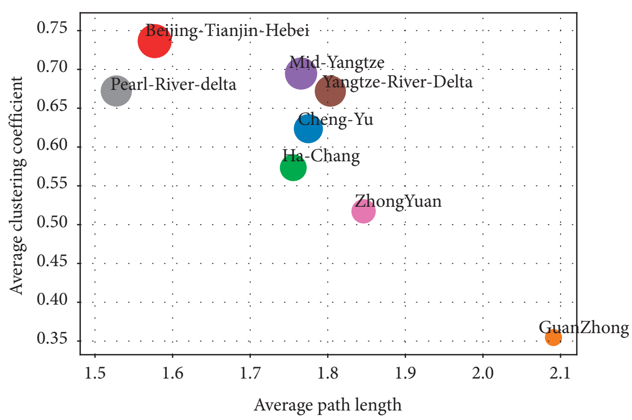


Figure 4: Average clustering coefficient, average path length, and density.

UAs is also relatively intermediate. This shows that urban economic linkages in this type are relatively close. Affected by APL, the exchange of economic resources is not as efficient as in BTH and PRD. From the perspective of the ACC, this type of UA is largely different in local economic connections. For example, YRD and MY have dense local economic linkages, while ZY is relatively sparse, which indicates these UAs are at a different development status. (3) UAs with high APL and low ACC. This only contains GZ, and it also has small network density and weak economic connections. The main reason for this is that it is located in Northwest China, far away from the oceans, and the transportation infrastructure is poor, so it has a low development level.

3.3. Centrality. Based on the comparison of overall topology properties, this section further analyzes the centrality of cities in each UA. Figure 5 shows the joint distribution of the DC and BC of cities in the eight UAs.

As shown in Figure 5, there is generally a clear correlation between DC and BC; that is, cities with higher DC also have higher BC. This indicates that cities with more UA resources also have a stronger ability to control the exchange of resources between other cities. We also found that there are many cities that have both high DC and BC in YRD and MY, indicating that these two UAs have formed a multicenter development status.

For each UA, a city with high DC means it has strong direct economic connections with other cities. According to the results, cities with high DC can be divided into two categories: (1) Highly developed cities, such as Guangzhou and Foshan in PRD, Beijing and Tiajin in BTH, and Suzhou, Wuxi, and Shanghai in YRD. These cities have a relatively significant position in their UA due to their high economic development level and frequent exchange of resources with surrounding cities. (2) Cities with a good geographical location that is near the central city, such as Langfang, which has the third largest DC in BTH. Its economic level is lower than Tangshan and Shijiazhuang, but its location is between Beijing and Tianjin, the most developed cities in the UA. Strongly influenced by these two cities, Langfang has a relatively important role in this area. Another example is Huanggang in MY. This is also a less developed city in an excellent geographical location. Huanggang is located near Wuhan, one of the center cities in MY, and it is only 7 km driving distance from Huanggang to Wuhan. Convenient transportation conditions strengthen the economic connections between the cities. Huanggang itself also has a large population, whose scale is only smaller than Wuhan in the Hubei province. With abundant labor resources, it has high DC and occupies a relatively important position.

Cities with high BC usually play the role of a “bridge” in a network and have a strong ability to control resources. According to the results, cities with high BC usually have high DC, such as Beijing and Tianjin in BTH and Guangzhou and Foshan in PRD. The surrounding cities and towns are connected to each other through these central cities. However, there are also some cities with relatively high BC that are not the core cities in the UA, like Deyang in CY and Xinxiang in ZY. They are not located at the geographical center of the region, and their centrality is not the highest, but they connect several well-developed cities and have greater development potential for the future.

In order to further study the centrality distribution of each UA, centralization was calculated. The results are shown in Figure 6.

The overall degree centralization of the eight UAs is not high, and the difference is small (mean: 15.45% and standard deviation: 7.67%). However, the BC is high and the differences are significant (mean: 53.47% and standard

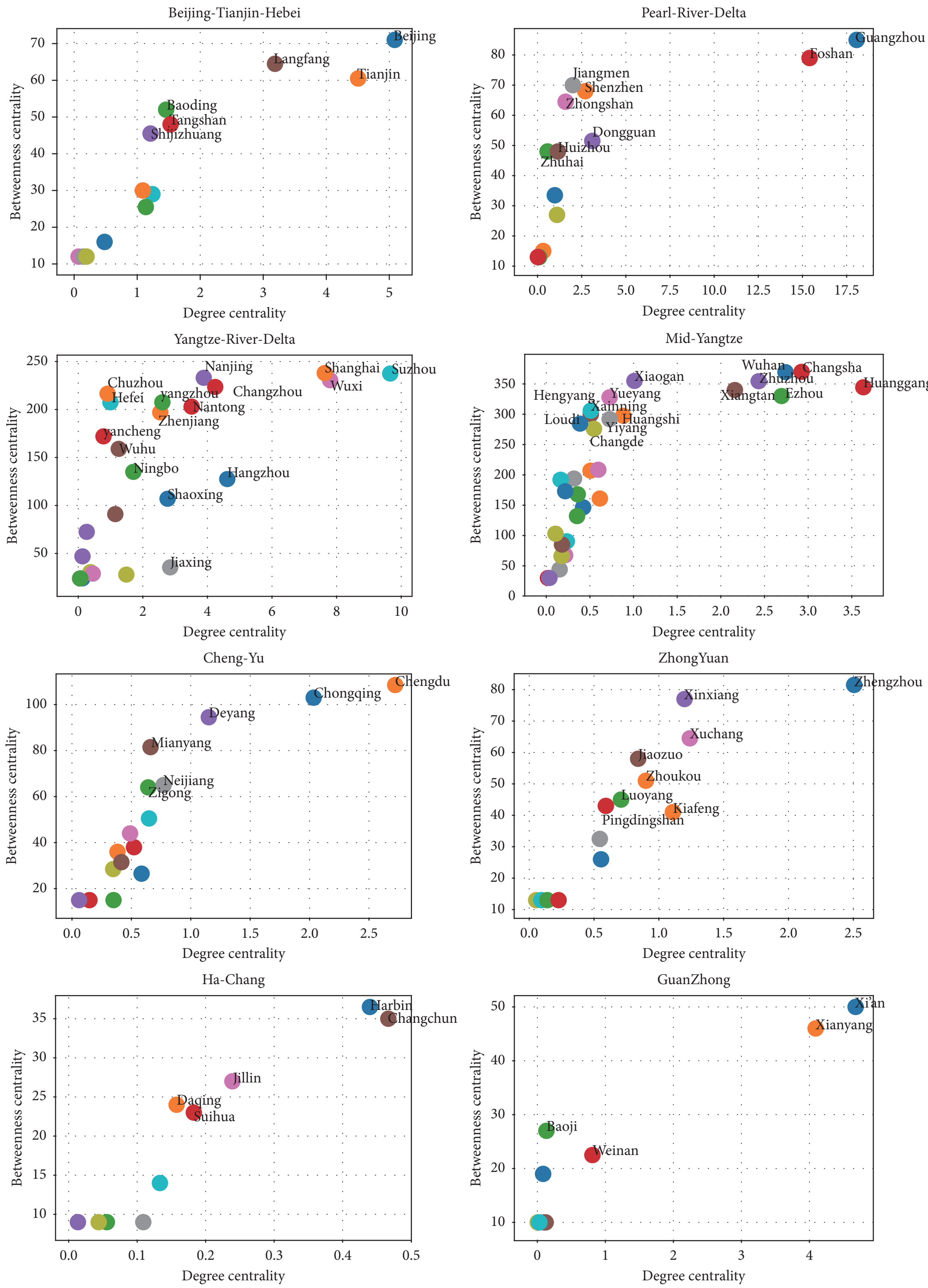


Figure 5: Degree centrality and betweenness centrality.

deviation: 11.04%). According to the distribution results in Figure 6, the eight UAs can be divided into the following three types.

3.3.1. UAs with High BC and Low-Degree Centralization. GZ belongs to this type, indicating that the cities in this UA have large differences in their ability to control the exchange

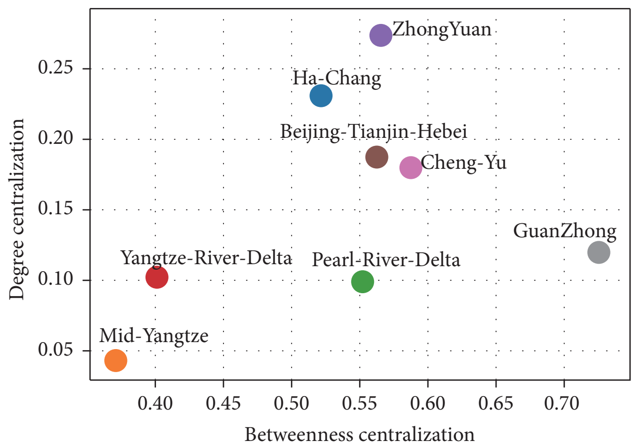


FIGURE 6: Degree centralization and betweenness centralization.

of resources between other cities. At the same time, its degree centralization is small, which means the resources occupied by each city are similar, and their economic development is relatively average.

3.3.2. UAs with Medium BC. This type of UA includes ZY, HC, CY, BTH, and PRD. The ability of cities to control the exchange of resources is at a moderate level. Among them, ZY and HC have larger degree centralization. Their central cities own more resources, and UA development mainly focuses on the central cities. CY and BTH have the third and fourth largest degree centralization, and their development also relies on the core cities. Degree centralization in PRD is relatively low, and the development level of its cities is similar.

3.3.3. UAs with Low BC and Low DC. This type includes YRD and MY. In these two UAs, the difference in the centrality of cities is relatively small, and their development tends to be polycentric. At the same time, cities with higher DC undertake a smaller share of BC than in other UAs. The role of the “bridge” is gradually transferred to peripheral cities.

Through the above indicators, we found that the BTH and PRD urban agglomerations show a state of concentration development. They have a large network density and small average path length. The relationships between cities are close. The large clustering coefficient indicates that their local aggregation degree is high, and economic connections are spatially concentrated around the central cities. YRD and MY show localized multicenter development. Their network density and average path length are middling, but their clustering coefficient is high. There are several central cities in these two UAs, and other cities are developing around the local center. The difference in city centrality is small. The CY, ZY, and HC urban agglomerations are at the stage of development around the central city. Their density, average path length, and clustering coefficient are all at a middling level. CY is centered on Chengdu and Chongqing. HC is centered on Harbin and Changchun. ZY has a high degree of centralization and is developing around Zhengzhou. GZ has long average path length and a small average clustering coefficient. Its overall network structure is loose, and the ability of each city to control and own resources is quite different. GZ is centered on Xi’an and Xianyang, but they cannot efficiently promote the development level of the surrounding cities.

3.4. Case Analysis. Based on the above findings, we observe two UA groups with similar network structures. BTH and PRD have the same small-world network characteristics. The connections in YRD and MY are both widely distributed. These two UA groups are located in China’s developed areas, and their development is relatively complete. The specific reasons for their similarity in economic network structure will provide reference for the future development of underdeveloped regions.

3.4.1. BTH and PRD. The BTH and PRD urban agglomerations show a state of concentrated development. From Figure 2, we can see the obvious economic concentration area. BTH is located in the Bohai Economic Belt, encompassing the most important international port in North China—Tianjin port. PRD is adjacent to Hong Kong and has an international port—Guangzhou port. Port trade drives the economic development of these two UAs. Thus, economic connections are concentrated in the area adjacent to the coastal ports. From the perspective of city degree centrality, these two UAs both have obvious leaders: Guangzhou and Foshan in PRD, and Beijing and Tianjin in BTH. As for BC, Tangshan, Beijing, and Shijiazhuang are the top three cities in the BTH urban agglomeration. Qingyuan, Shenzhen, and Huizhou are the top three cities in PRD. The bridge role of central cities has been transferred to the surrounding cities. The transfer in BTH was less thorough than that in PRD, as Beijing still has high BC. From Figure 5, the degree centralization of BTH is greater than that of PRD, indicating that the development of BTH is more concentrated.

From the economic and social indicators (Table 4), we can see that the economic development levels and population scales of these two UAs are similar. The GDPs for both are around 7.5 trillion Yuan, and the population densities for both are around 450 people/km^2. In terms of the development model, all cities in PRD are under the jurisdiction of the Guangdong province, so they are coordinated in terms of policy formulation and division of labor. The cities in BTH are in different provinces. They mainly depend on Beijing, China’s capital city, to coordinate regional interests, which leads to the difference in city centrality.

In the process of UA development, it is important for central cities to play a leading role and cultivate economic concentration areas around central cities. At the same time, in order to relieve the heavy burden of central cities, we should actively cultivate the next economic growth point.

3.4.2. YRD and MY. YRD and MY show localized multicenter development. From Figure 3, we can see that the economic connections between these two UAs are scattered, and the difference in city centrality is small. These two UAs

Table 4: Economic and social indicators in Beijing-Tianjin-Hebei and the Pearl River Delta.

Urban agglomeration	Gross domestic product (GDP) (billion)	Population (million)	Land area (km^2)	Number of cities
PRD	7301.73	51.36	120,706	14
BTH	7523.76	101.11	214,863	13

Table 5: Economic and social indicators in the Yangtze River Delta and Mid-Yangtze.

Urban agglomeration	GDP (billion)	Population (million)	Land area (km^2)	Number of cities
YRD	14,301.75	124.94	207,316	25
MY	7254.19	134.36	351,316	31

are both in the Yangtze River Economic Belt. The east of YRD is adjacent to the ocean, and it contains important ports such as Shanghai port and Ningbo port. It is an important window for China's foreign trade, similar to PRD and BTH. This factor has led to the economic connections in the network being concentrated in the eastern coastal areas. MY is located inland and is not adjacent to the ocean. It mainly relies on the Yangtze River for inland water transport. Wuhan is the most important port of the Yangtze River, so we can see economic links concentrating in Wuhan. Changsha, the capital city of the Hunan province, is in the south of this UA; it plays an important administrative role and also attracts the concentration of the southern economy.

From the perspective of the development model, the cities in these two UAs are under the administration of different provinces. In the process of UA development, cities are mainly closely connected with the provincial capitals, and they are connected with each other through the capitals. In this way, the local centers of these two UAs are formed.

From the social and economic indicators (Table 5), we can see that the GDP of YRD is 14.3 trillion Yuan, which is twice that of MY. In terms of population density, YRD has a density of 603 people per square kilometer, and MY has a population density of 382 people per square kilometer. The population density of YRD is 1.5 times that of MY. As for the scale, YRD has 25 cities and MY 31 cities. These economic and social conditions mean that the connection strength in YRD is larger than that in MY. This can be clearly seen in Table 2 (the average weighted degree of the economic network in YRD is significantly larger than that in MY). Therefore, although these two UAs have the same network structure, they are at different development levels and the strength of their connections is also very different.

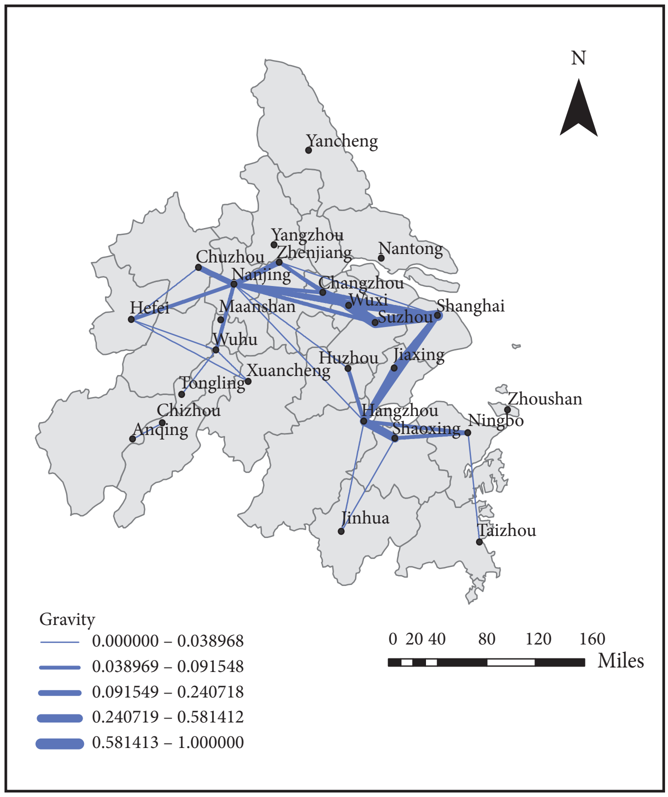
When the cities in UAs are located in different administrative regions, an economic concentration area forms around the local central cities, and they connect with each other through the central cities; thus, the network is polycentric. However, a UA with this network structure may not necessarily have a high level of development. We should also pay attention to the weight of the connections.

4. Discussion

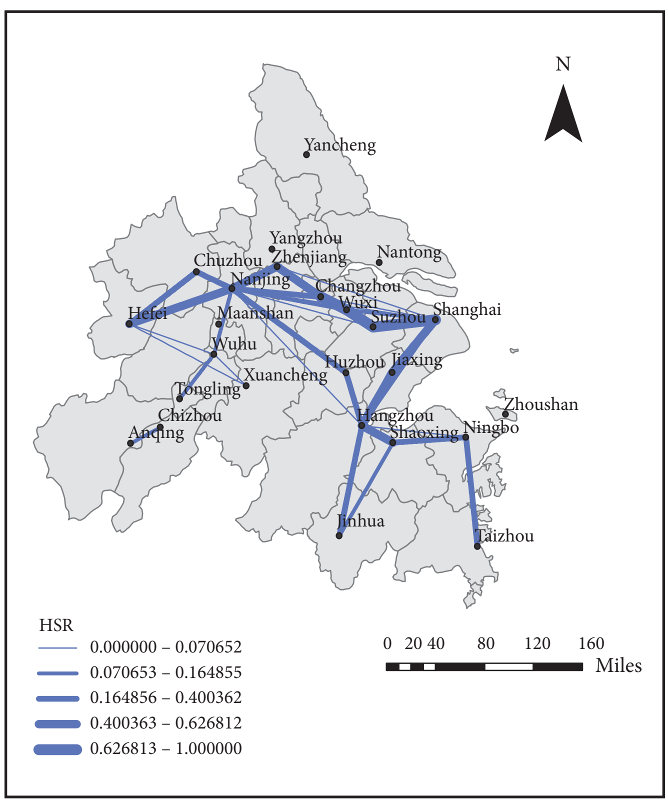
4.1. Comparison with the Empirical Flow Data. To find out the association between the city network obtained by the gravity model and empirical flow, we collect the high-speed rail (HSR) timetable data and Baidu index data (a city's search volume in another city) of the YRD. The HSR data reflect the transportation flows, and Baidu index represents the information connections between cities. Based on the above data, we constructed the gravity, transportation, and information networks. The edge weight in the gravity network is obtained from the gravity model. In the transportation network, the edge weight is defined as the number of HSR trains passing between two cities in a day, and the edge weight in the information network is defined as the total search volume for each other's names between two cities per day. The weight of the connections in the three networks is normalized between 0 and 1. Their spatial organizations are compared in Figure 7. The city pairs with the highest weight and the lowest weight are listed in Table 6. Table 7 lists the ranking of cities by DC and BC in the three networks. Particularly, because not all cities have high-speed rail stations in the YRD (2016), we only retain the city pairs that have HSR trains.

The results indicate that the spatial distribution of cities in gravity network is similar as that in the empirical network. (1) From the perspective of edge weight (Table 6), we can see that the ranking of city pairs with highest and lowest edge weight is similar. Suzhou-Shanghai has relative high edge weight in all the three networks, ranking second in the gravity network and first in the transportation and information networks. The city pair with the lowest edge weight in the gravity network is Xuancheng-Hefei, which is the same as in the transportation network. (2) In terms of DC (Table 7), the ranking of cities in the gravity network also shares some similarities with the empirical network. For example, Suzhou ranks top three in all the three networks, and Hangzhou ranks fourth both in gravity and empirical networks. Besides, the cities with the lowest DC in the three networks are Xuancheng, Taizhou, Chizhou, Anqing, and Tongling, though the exact rankings of these cities are slightly different. (3) From the perspective of BC, the bottom six cities with the lowest BC are ranked the same in the three different networks, namely, Jinhua, Xuancheng, Taizhou, Tongling, Chizhou, and Anqing. From the analysis results of edge weight, DC and BC, we can find that the spatial organization of cities in the gravity network shares some similarities with the urban structure presented by the empirical network. Thus, the gravity model can be considered as an effective method in approximating the interaction between cities in UAs.

Through the comparison of edge weight, DC and BC, we find that the ranking of cities in the three networks is similar; however, ranking cannot fully indicate the distribution of city centrality. It cannot illustrate the differences of centrality between the central city and other cities. Therefore, the centralization of the gravity, transportation, and information networks are calculated (Table 8). The results

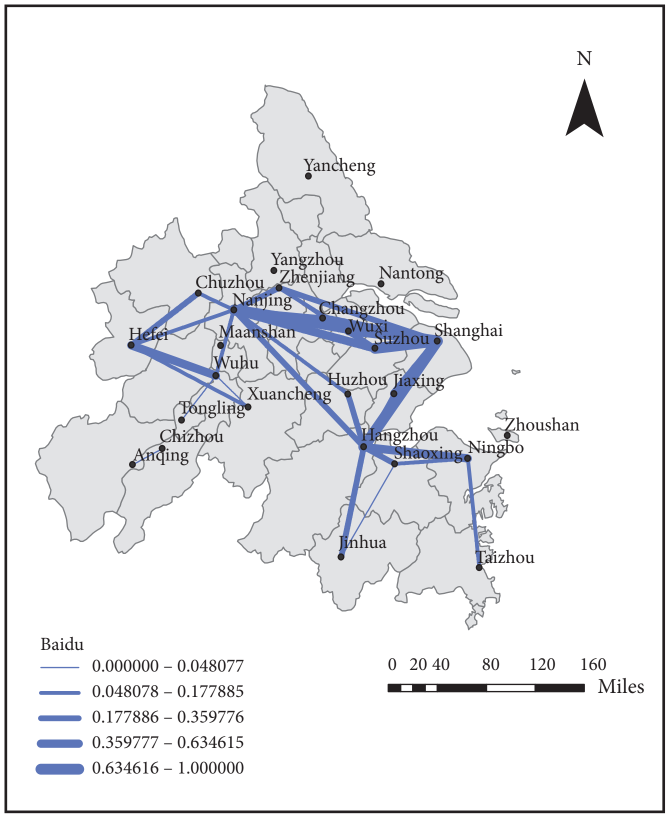


(a)



(b)

Figure 7: Continued.



(c)

Figure 7: Spatial pattern of cities within YRD. (a) Cavity model. (b) HSR timetable data. (c) Baidu index.

Table 6: List of city pairs by weight.

Ranking	Weight		
	Gravity	HSR	Baidu
1	Wuxi-Suzhou	Suzhou-Shanghai	Suzhou-Shanghai
2	Suzhou-Shanghai	Wuxi-Suzhou	Shanghai-Hangzhou
3	Wuxi-Changzhou	Wuxi-Changzhou	Shanghai-Nanjing
34	Wuhu-Tongling	Nanjing-Hangzhou	Wuhu-Tongling
35	Nanjing-Huzhou	Zhenjiang-Shanghai	Shaoxing-Jinhua
36	Xuancheng-Hefei	Xuancheng-Hefei	Chizhou-Anqing

indicate that the distribution of city centrality in the gravity network is more similar to that in the transportation network, and its distribution is more even than in the information network. Specifically, the value of degree centralization is 0.090 in both gravity and transportation network. The betweenness centralization of gravity network is 0.330, and it is 0.337 for transportation network. It indicates that the distribution of degree and betweenness centrality in gravity and transportation network are relatively similar. In the information network, the degree and betweenness centralization are 0.212 and 0.512, which is higher than in gravity and transportation network. It indicates that although the ranking of centrality is similar in the three networks, the distribution of centrality tends to be more concentrated in the information network and more evenly in gravity and transportation networks. In a word, the calculation results of the centralization show that the spatial structure of city network constructed by the gravity model is closer to the structure reflected by the transportation flows.

By comparing the edge weight, centrality, and centralization, respectively, in gravity, transportation, and information networks, the city network constructed by the gravity model can represent the empirical network approximately. Besides, the spatial pattern presented by the gravity model is more similar to the pattern reflected by the transportation flows. Thus, when the acquisition of empirical flow data of all cities is difficult and the analytical scope is limited, the gravity model can be used to incorporate all cities in the analysis and reflect the spatial organization structure of the cities. In addition, the gravity model can also be used to inform the potential connection and future change of empirical flow as it is driven by scaler factors that can be projected in-line with the future socioeconomic plan. It would be more valuable if the gravity model can be calibrated by historical empirical data to predict the potential connection and future trend between cities.

4.2. Policy Implications. Based on the horizontal comparison of China's eight major UA networks, we posit several policy

Table 7: List of cities by DC and BC.

Ranking	Degree centrality			Betweenness centrality		
	Gravity	HSR	Baidu	Gravity	HSR	Baidu
1	Suzhou	Nanjing	Shanghai	Shanghai	Nanjing	Shanghai
2	Wuxi	Suzhou	Nanjing	Suzhou	Suzhou	Nanjing
3	Shanghai	Wuxi	Suzhou	Wuxi	Shanghai	Hangzhou
4	Hangzhou	Hangzhou	Hangzhou	Nanjing	Wuxi	Suzhou
5	Changzhou	Changzhou	Wuxi	Hangzhou	Jiaxing	Hefei
6	Nanjing	Shanghai	Changzhou	Changzhou	Hangzhou	Wuhu
7	Shaoxing	Zhenjiang	Hefei	Zhenjiang	Changzhou	Ningbo
8	Jiaxing	Shaoxing	Zhenjiang	Jiaxing	Zhenjiang	Wuxi
9	Zhenjiang	Jiaxing	Ningbo	Wuhu	Shaoxing	Chuzhou
10	Ningbo	Hefei	Wuhu	Chuzhou	Wuhu	Shaoxing
11	Chuzhou	Huzhou	Jiaxing	Shaoxing	Hefei	Zhenjiang
12	Wuhu	Chuzhou	Shaoxing	Hefei	Huzhou	Changzhou
13	Hefei	Ningbo	Huzhou	Ningbo	Ningbo	Jiaxing
14	Huzhou	Jinhua	Chuzhou	Huzhou	Chuzhou	Huzhou
15	Jinhua	Wuhu	Jinhua	Jinhua	Jinhua	Jinhua
16	Xuancheng	Taizhou	Xuancheng	Xuancheng	Xuancheng	Xuancheng
17	Taizhou	Tongling	Taizhou	Taizhou	Taizhou	Taizhou
18	Chizhou	Chizhou	Tongling	Tongling	Tongling	Tongling
19	Anqing	Anqing	Chizhou	Chizhou	Chizhou	Chizhou
20	Tongling	Xuancheng	Anqing	Anqing	Anqing	Anqing

Table 8: Centralization in the gravity, transportation, and information networks.

	Gravity	HSR	Baidu
Degree centralization	0.090	0.090	0.212
Betweenness centralization	0.330	0.337	0.512

recommendations for improving UA's development level and competitiveness.

For UAs such as BTH and PRD, which show a state of concentrated development, the central cities may bear the burdens of large population, causing serious urban problems such as traffic congestion. Therefore, it is necessary to combine the development of surrounding cities with alleviating the population pressure of central cities. For example, in BTH, the bridge role of Langfang can be fully utilized to undertake the population and industrial transfer from Beijing and Tianjing, alleviating the contradiction between population and resources in central cities and cultivating Langfang to be a new growth pole.

Although YRD and MY both present a polycentric network structure, their development levels vary widely. For YRD, in order to avoid the unhealthy competition caused by role orientation identically, the role of each city should be clarified, and their conflicts should be coordinated. Although MY also presents a polycentric structure, its development level is far less than YRD. The focus of its future development is to expand the influence of its central cities, break the barriers of administrative divisions, and strengthen exchanges and collaboration between central cities of each region. Measures can be taken such as reducing the transprovincial and transcity transaction costs.

UAs such as CY, ZY, and HC are at a stage of development around the central city. There exists a development gap between central cities and surrounding cities. In order to narrow this gap and promote the economic development level of small cities, the radiation effect of central cities should be made the best of. According to the research results, the BC will gradually transfer to surrounding cities. Therefore, cities with relative high BC in these UAs such as Deyang, Xinxiang, and Jilin could be guided to be the next growth pole.

UAs show a relatively loose UA network structure like GZ should mainly focus on cultivating regional centers that can lead the development of the whole area. For GZ UA, the integration strategy of Xi'an-Xianyang should continue to be promoted so that the economic influence of "Great Xi'an" can be enhanced.

5. Conclusions

UA is a self-organized system, whose development will normally be regular. The UAs of different development levels will present different spatial organization structures. The study of the interaction between cities will help to strengthen the functional connections in UAs. In this study, we constructed the economic network of China's eight urban agglomerations by introducing the gravity model. Then, we analyzed the overall structural characteristics and city centrality of their networks. To find out the association between the gravity model and empirical data, we compared the city networks constructed by the gravity model, transportation, and information flow. Finally, based on the analysis result, some policy implications for improving the development level of UAs were proposed. We mainly come to the following conclusions.

UAs with different development levels present different spatial network structures, but the network structures cannot reflect the development levels of UAs directly. By evaluating the interaction of cities in the eight UA areas, the different spatial network structures can be established. For example, BTH and PRD urban agglomerations show a state of concentrated development. CY, ZY, and HC urban agglomerations are at a stage of development around the central city. However, UAs who have similar network structure do not mean they have similar development levels. YRD and the MY both show localized multicenter development, but their development level differs. Thus, when a UA spans different province and has a uniform multicenter network, this does not mean the UA has a high level of development. The weight of the connections must be considered.

The cities with high betweenness centrality have greater development potential. First, BC and DC have a high degree of correlation in UA networks, which indicates that the core cities usually play the role of "bridge" between cities. Second, in the process of UA development, BC gradually transfers from the central city to the surrounding cities. Therefore, the cities that undertake the role of "bridge" are more likely to be the next growth pole in the UA.

The city network constructed by the gravity model can represent the empirical network approximately. The network indicators, such as DC, BC, and centralization, are similar in the gravity network and empirical network. Besides, the spatial pattern of UA presented by the gravity model is closer to the pattern reflected by the transportation flows. Thus, when the acquisition of empirical flow data of all cities is difficult and the analytical scope is limited, the gravity model can be used to incorporate all cities in the analysis and reflect the spatial organization of the cities.

As for the limitations of data acquisition, there are limited main factors in the gravity model. In future studies, more factors that have an impact on the UA network structure, such as environment and culture, should also be considered in the gravity model. Thus, a more in-depth impact mechanism of UAs in China will be discussed in the next study. Besides, the gravity model reveals the connections and its spatial structure in the UAs, but its specific differences from the empirical UA network are still unknown. The further research can compare the differences between the gravity network and empirical network in more detail. In this way, the specific impact of each type of flow data on the UA network can be clarified, and precise measures can be implemented to guide the sustainable development of UAs. Finally, we only reveal the spatial organization of different UAs in this paper. A detailed investigation of the mechanism of interaction between cities and its correlation with the industrial structure of each city is needed in future research so that more practical policy implications can be proposed to enhance the competitiveness of UAs.

Data Availability

All data generated or analyzed during this study are included in this manuscript and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Q.S established the research framework; S.W and K.Z. jointly established the research model; F.M, X.G, and T.L collected the data and carried out the result calculations; Q.S provided the data acquisition channel; and Q.S and S.W analyzed the results and wrote the paper together.

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