The spatial connection network pattern of urban agglomerations in the Pearl River Delta

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Abstract. Urban agglomeration is a spatial form of highly developed comprehensive cities and an important driving force for regional economic development. Based on the data of highways, regular-speed trains, high-speed trains and Baidu index data among 9 cities in the Pearl River Delta, this paper uses spatial visualization and social network analysis to study the spatial connections and network patterns of urban agglomerations from multi-factor flows. The results show that the spatial connection between cities in the Pearl River Delta mainly radiates outward from Guangzhou, Shenzhen and Dongguan, and connects with the network formed by secondary cities such as Foshan, Huizhou and Jiangmen. A multi-core development urban network pattern is formed by an absolute core circle and a peripheral low-density circle. The core circle is consist of Guangzhou-Shenzhen-Dongguan, and the low-density circle is consist of 6 city nodes with low degree value. The development of regional integration can strengthen the cooperation and exchange among cities, and it also can optimize the spatial structure of the urban agglomeration network.

1. Introduction  
In the context of economic globalization and regional economic integration, urban agglomerations not only determine the future development of the regional economy, but also determine the role and status of country in the global economic structure. At present, the evolution of the spatial structure of urban agglomerations becomes more complicated due to the increasingly developed communication and transportation facilities, and urban agglomerations show the characteristics of networked connections [1]. Urban agglomeration refers to a relatively comprehensive urban "aggregate" constructed in a specific area with one or more megacities as the regional economic core, relying on modern transportation methods and highly developed information networks. Infrastructure networks such as transportation and communications can help form urban agglomerations with close economic ties and highly integrated characteristics. Compared with a single city, the advantage of Urban agglomeration lies in their ability to accelerate the flow of resources, strengthen industrial cooperation and break administrative restrictions. Therefore, urban agglomerations will become an important driving force for future economic development. However, affected by geographical location, natural resources, and development policies, the interconnected structure and spatial organization of urban agglomerations are very unique, resulting in different levels of urban agglomeration development. In order to clarify the direction of urbanization construction and promote the development of underdeveloped areas, it is of great practical significance to study the spatial connections and functional networks of each existing urban agglomeration.
Traditional urban spatial organization research discusses the development of urban clusters on the basis of the central place theory, emphasizing the leadership of cities, while ignoring the mutual assistance and cooperation between cities. With the development of economic globalization and regional economic integration, the concept of urban networks breaks the limitations of traditional theories and provides a new way to understand the relationship between cities. Castells\cite{2} proposed the concept of "flow space", which expresses a way of sharing social resources without relying on the proximity of space, and the network modeling of functional connections between cities appears.

At present, many researches about "space of flows" and Urban Network focused on traffic and transportation flow\cite{3,4}, information transmission flow\cite{5,6,7}, industrial organization relationship flow\cite{8}, and capital flow\cite{9} have studied by many scholars. These studies have deepened our understanding of the interaction between cities provided a reference for the study of urban networks in small areas. For example, Taylor\cite{10} established an interlocking networking model, which combines diverse urban data to study the connections between the world, countries or regions under multiple scales. Guimera\cite{11} uses global aviation data to study urban networks and the role played by the city; Grubesic\cite{12} et al. quantified the accessibility of the city through Internet facilities. In recent years, domestic scholars have revealed the network structure of the urban system through different factor flows at different research scales. For example, An Yujing\cite{13} et al. analyzed the spatial organization structure of the Yangtze River Delta by combining multi-factor flows. Jiang Daliang and Sun Ye\cite{14} used Baidu Index to construct the spatial pattern of the information flow network within the urban agglomeration.

On the whole, the existing urban network research mainly presents the characteristics of diversified perspectives and methods and focused more on exploring the urban spatial pattern under a single economy or a single factor flow, but study less in exploring the urban network pattern under the effect of multiple factors flows. The Pearl River Delta, a typical representative of China's regional economic development, is one of the Urban agglomeration representatives with the fastest growth in traffic information in recent years. Under the current background of the development of big data, its regional spatial network pattern may undergo major changes.

In view of this, this article uses the Pearl River Delta urban agglomeration as the research area. A comprehensive regional network based on highways, ordinary-speed railways, high-speed railways and information network data is built to explore the characteristics of the regional network structure under the combined effect of multiple factor streams. It is expected to provide scientific support for the overall coordinated development and spatial structure optimization of the urban agglomeration in the Greater Bay Area.

2. Theories and Date

2.1. Research location

According to the "Pearl River Delta Development Plan" issued by the Central Committee of the Communist Party of China and the State Council, the Pearl River Delta includes the Hong Kong Special Administrative Region, the Macau Special Administrative Region and Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou and Dongguan, Zhongshan City, Jiangmen City, Zhaoqing City
2.2. Data sources
The original data in this paper are the passenger traffic frequency of automobiles, regular-speed trains, high-speed trains and Baidu index among 9 cities in the Greater Bay Area. The data of ordinary trains (numbers starting with K, Z, T and 4 digits) and high-speed trains (numbers starting with G/D/C) are from the 12306 Railway Customer Service Center (www.12306.com), and the data of car frequencies are from the source on the 114 fare network (www.keyunzhan.com). Due to the relatively fixed schedule of road and railway trips, 1d (November 18, 2020) data is selected as a representative. The information network data is searched and obtained through the "regional comparison" function of the "Baidu Index" interface, and selected the monthly average of user attention between two cities in November 2020. and the monthly average of user attention between two cities in November 2020 is selected. The shortest travel time data between two cities is extracted based on normal-speed trains and high-speed trains. The shortest time-consuming transit route between cities without direct trains is extracted according to the principle of the shortest time and shortest distance, and transit and stay time is not taken into consideration. The shortest road arrival time comes from the shortest arrival time between two cities on the Baidu map. The economic data involved in the article comes from the "Guangdong Statistical Yearbook-2019"[15].

2.3. Research methods.
This paper adopts a social network analysis model to study the network structure of urban agglomerations, and the analysis is based on the strength of relationships between cities. At present, most scholars use the gravity model constructed by urban GDP and population[16-18] to calculate the strength of urban relations. Due to the two indicators are simply used, the analysis results are one-sided and cannot measure the comprehensive capabilities of the city. The intensity of urban flow is the intensity of factor flow generated when economic agglomeration and diffusion occurs between cities. It uses the level of labor to calculate the capacity of each region in each industry to provide services to other regions, thereby more fully reflecting inter-regional factors flow environment and capabilities. Some studies use the urban flow intensity model to identify and compare the spatial structure of urban agglomerations. Other studies have verified that urban flow intensity can reflect the closeness of inter-regional connections, which is a more reliable indicator of spatial relationship description. Therefore, this article introduces the urban flow model into the basis of the general gravity model to quantitatively study the comprehensive capabilities of cities. The improved gravity model measures the relationship between cities and reflects the exchange of factors such as production, life, information, and technology between cities. And interaction, in order to study the network characteristics of urban
agglomerations more comprehensively.

(1) The expression of the general gravity model is shown in formula (1) [19-21]

\[ R_{ij} = \frac{m_i \times m_j}{D_{ij}^b} \]  

where \( R_{ij} \) is the closeness of the relationship between city \( i \) and city \( j \); \( m_i \) and \( m_j \) are the quality of cities \( i \) and \( j \) respectively; \( b \) is sparse distance friction; \( D_{ij} \) is the distance between the two cities.

(2) The formula for measuring urban flow intensity [22]

\[ F = N \times E \]  

Where \( N \) is the functional benefit of city, that is, the actual impact produced by the external functional capacity of unit between cities; \( E \) is the external functional capacity of the city, reflecting the size of the city's external functional capacity.

3. Analysis of the spatial connection network pattern of urban agglomerations in the Greater Bay Area

3.1. Road passenger transport network

The 9 cities in the Pearl River Delta constitute 72 road Road passenger transport network. First, the density of inter-regional connections is analyzed. Compared with the other three cities, the six cities, Guangzhou, Shenzhen, Dongguan, Foshan, Zhongshan, and Foshan, have higher inter-city connections, and the frequency of road transportation is also higher. In terms of the strength of the connection, the City-pair with strong connections are Guangzhou-Shenzhen, Zhuhai-Guangzhou, Shenzhen-Dongguan, and Guangzhou-Dongguan. The transportation efficiencies of the four city-pair are respectively 0.815 min/km, 0.878 min/km, 1.068 min/km, 1.089 min/km.

3.2. Common Slow Train Network

There are 31 common slow train networks in 9 core cities of the Pearl River Delta. In the perspective of inter-regional connection density, the cities along the Guangzhou-Shenzhen Railway, such as Guangzhou, Dongguan, and Shenzhen, have frequent connections and strong connection density. Among them, Guangzhou-Shenzhen and Dongguan-Shenzhen have relatively high connections, and the average daily trains are about 35. This is mainly due to the "Guangdong-Shenzhen" railway connecting the intra-regional network of the urban agglomeration in the Pearl River Delta.

3.3. Express train network

There are 60 high-speed train networks in the 9 core cities of the Pearl River Delta. Compared with common slow train networks, high-speed trains are more closely connected. In the perspective of inter-regional connection density alone, High-speed trains not only have a high connection density in cities around the Guangzhou-Shenzhen line, but increase and expand the connection density and urban space of Guangzhou-Zhuhai, Zaoqiong-Huizhou, Guangzhou-Jiangmen and other cities. In the perspective of inter-city connections, not only the connection density among Guangdong and Shenzhen is relatively high, but also the connection density between Guangzhou-Zhuhai, Zaoqiong-Foshan, Guangzhou-Zhongshan and other cities. In the perspective of the connection lines density among cities, the strongest connection within the urban agglomerations of the Pearl River Delta is Guangzhou-Shenzhen, with 187 regular-speed trains running daily, followed by Guangzhou-Foshan and Zhongshan-Zhuhai, 180 high-speed trains and 104 high-speed trains are operated daily.

3.4. Information flow

The number of information networks in the 9 core cities of the Pearl River Delta urban agglomeration is 72. In the perspective of inter-regional contact density, the contact density of information network in the Guangzhou, Shenzhen, Dongguan, Zhongshan, Zhuhai, and Foshan is higher than that of other three cities. In the perspective of the contact strength of each City-pair, the information network connection of
Guangzhou-Shenzhen is 1096, Shenzhen-Huizhou is 748, Guangzhou-Foshan is 746, and Guangzhou-Zhuhai is 696.

On the basis of the above urban networks, it can be seen that road transportation and high-speed rail information networks constitute the basic context of the spatial network of the Pearl River Delta. However, due to comprehensive factors such as city scale, economic development level, and inter-city high-speed rail, the time-space differences in urban time between cities is reduced. The development of Regional integration is further accelerated, and the external connection network of cities is broadened.

Fig. 2. Network connection of the four major elements in the Pearl River Delta

4. Comprehensive Contact Network and its Organizational Structure Analysis

4.1. City correlation analysis

The original data is standardized by formula (1) and (7), and highways, high-speed railways, general-speed railways, and information flows are given equal weight to construct a comprehensive urban network connection matrix in the Greater Bay Area. The comprehensive connection network diagram (Fig. 3) of Greater Bay Area is visualized by ArcGIS. The comprehensive network density of the urban agglomerations in the Greater Bay Area is 0.42. The urban spatial network mainly radiates outward with Guangzhou, Dongguan, and Shenzhen as the core, and secondary cities such as Foshan, Huizhou, and Jiangmen form connections. Its radiation flows mainly in Guangzhou-Shenzhen, Guangzhou-Dongguan, Shenzhen-Dongguan and other cities, and the urban spatial network of the
Greater Bay Area presents a multi-core development model. Judging from the comprehensive connection network diagram of the urban agglomeration in the Greater Bay Area, the regional connection density takes Guangzhou-Dongguan-Shenzhen as the core circle, and gradually decreases in the outer layer. In addition, the connection density in the eastern part of the entire Bay Area is significantly higher than that in the western part. Therefore, the uneven spatial structure of the urban agglomerations in the Greater Bay Area is prominent. The entire region presents a "core-edge" structure. The cluster spatial structure shows a positive correlation. For example, Zhaoqing and Jiangmen have low per capita GDP, and these two cities are at the edge of the entire spatial structure. Combining with the four element maps and the comprehensive connection network map of the Greater Bay Area urban agglomeration, it can be seen that Guangzhou-Shenzhen-Dongguan is an important node of the entire urban agglomeration network and plays a guiding role in the development of regional integration. On the one hand, the development model of the Greater Bay Area has strengthened the radiation effect on surrounding cities and promoted the economic development of the Greater Bay Area. On the other hand, several fringe cities with lower degree value move closer towards the core circle in the regional integration policy. By increasing the exchanges between cities, they constantly gain more development space.

![Fig. 3. Comprehensive network of urban agglomerations in the Pearl River Delta](image)

4.2. Centrality analysis
The Ucinet 6.0 software is used to calculate the structural characteristic parameters of the comprehensive connection network of the urban agglomeration in the Pearl River Delta, and ArcGIS 10.3 is used for spatial visualization (Figure 4). It can be seen that the regional agglomeration characteristics of the high-level centrality area are obvious. Guangzhou-Shenzhen-Dongguan forms the core circle of the urban agglomeration network, and other six cities, such as Foshan, Zhuhai, Zhaoqing, Zhongshan, Jiangmen, and Huizhou, form the border circle. The "core-periphery" structure of the entire urban agglomeration network is obvious. Among them, Guangzhou's dominant position is stable, and the communication capacity of high-value internal cities is significantly higher than that of other cities, further demonstrating the obvious integration phenomenon of the Greater Bay Area. It can be seen from the functional circle and radiation influence range of each city that Guangzhou is in an absolute dominant position, and Foshan and Zhaoqing are heavily influenced by Guangzhou. This is the same as the previous policy of "Guang-fo-Zhao integration". The phenomenon of two-level differentiation shows that the cities in the core circle have a strong grasp of regional integration. This kind of
differential attraction to population caused by intercity traffic, information network and city functions with different characteristics. While strengthening the population agglomeration effect, it also spreads the people flow to the surrounding small and medium-sized cities. Thus, modern cities are urged to continuously expand urban cyberspace under the action of "spatial flow". With "spatial flow" as the carrier and the flow of "people" as the core, various information technologies not only promote the concentration and dispersion of human resources inside and outside region, but also promote the development of urban networks. The increasingly perfect urban rapid transportation network, especially the seamless connection of subways, intercity railways and high-speed railways, together with mobile communication technology, effectively supports the demand for enhanced economic and social connections inside and outside city, and will eventually enters a new era of " fluid space" based on mobile information technology [23]. Undoubtedly, the “flow” and “openness” of space brought by the powerful social power will have a positive impact on the reconstruction and networking of the national and regional urban systems [24].

Fig. 4. Spatial expression of urban degree centrality and Betweenness centrality in the Pearl River Delta

5. Conclusion
This paper analyzes the urban spatial connections and network pattern of the Greater Bay Area from the perspective of multiple comprehensive factor flow by selecting highways, regular-speed trains, high-speed trains and Baidu index data of 9 cities in the Pearl River Delta. The following conclusions are drawn.

First, the spatial connections among cities in the Pearl River Delta mainly radiate outward from Guangzhou, Shenzhen, and Dongguan as the core, and connects with the network formed by secondary cities such as Foshan, Huizhou, and Jiangmen. Cities at different levels have different effects in the future development of regional spatial structure. Among them, the Guangzhou-Dongguan-Shenzhen connection line is the most closely connected region, which will play a guiding role in the development of the spatial structure of urban agglomerations in the future. Cities such as Zhongshan and Foshan, play the function of connecting "transit stations". On the one hand, Guangzhou, Shenzhen, and Dongguan are the radiation areas of the core cities, which are responsible for higher-level functions and services from the leading cities to help their own economic development. On the other hand, neighboring cities in the core radiation area produce material exchanges at the production and consumption levels to form an urban system, which radiates peripheral cities and affects the overall spatial structure of the region.

Second, it has formed an urban network pattern consisting of an absolute core circle composed of Guangzhou-Shenzhen-Dongguan and a peripheral low-density circle composed of other six city nodes with low degree. The overall pattern is multi-core development. The current spatial structure of urban agglomerations in the Pearl River Delta presents an obvious “core-periphery” structure. However, with the globalization trend and the strengthening of regional integration policies, the development
opportunities of regional fringe cities will increase in the future. In the future, exchanges and cooperation among cities will be more extensive, promoting a more balanced development of urban agglomerations in the Greater Bay Area. At that time, the agglomeration effect of the urban agglomeration in the Greater Bay Area will continue to be transformed into a diffusion effect. The spatial structure of the region will change from an unbalanced “core-periphery” to a balanced “network-node” pattern. The mobility of capital, technology, information and labor in the region is increasing. The increasing mobility in the region will greatly enhance the ability of the Greater Bay Area city clusters to absorb and allocate resources on a global scale, and help the Greater Bay Area city clusters move towards a networked development era.

Third, the development of regional integration can strengthen the cooperation and exchange among cities and optimize the spatial structure of the urban agglomeration network in the Greater Bay Area. The fluidity radiation area of each city in the Greater Bay Area is clearly integrated, and the spatial form of the radiation influence areas of each city also indicates the functional circle and sphere of influence of each city. Foshan and Zhaoqing are greatly affected by the radiation of Guangzhou. The liquidity radiation areas of Shenzhen, Dongguan and Huizhou are intertwined. Cities such as Zhuhai, Jiangmen and Zhongshan are in the marginal zone.

Based on multivariate factor stream data, this paper analyzes the spatial connections and network patterns of urban agglomerations in the Pearl River Delta, and makes a preliminary discussion on its influencing factors, which can provide references for the study of regional spatial structure. The analysis of the urban agglomeration network based on the traffic information flow only represents a quantifiable perspective, but cannot absolutely reflect the real connections within the region. Undeniable, the information flow of highways, railways, and Baidu can more closely connect different levels of city nodes in the urban agglomeration, and enhance and optimize the spatial connection network structure to a certain extent. However, due to the time-sensitive characteristics of passenger traffic and Baidu index data, data change and update rapidly, and the acquisition of real-time updates and accurate data is quite limited. Thus, the research results have certain limitations. Based on data availability considerations, only provincial-administered cities are selected as the basic research unit, and the flow data of sub-administrative units such as counties and towns cannot be counted, which is not conducive to in-depth analysis of the detailed characteristics of the regional connection direction and spatial structure. In addition, the evaluation and correlation mechanism of economic output efficiency in cyberspace are also the direction to be further studied.

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