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Evolution and Evaluation of the Guangzhou Metro Network Topology Based on an Integration of Complex Network Analysis and GIS

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Abstract: This paper takes the metro network of Guangzhou as a case study, and provides a quantitative analysis of the historical development of the network from 1999 to 2018. Particularly, the evolution of the topological structure of the Guangzhou Metro Network (GMN) is evaluated and characterized through the integration of geographic information system (GIS) and complex network analysis. The results show that: (1) The metro network of Guangzhou possesses the basic characteristics of small-world network, (2) with the development of GMN, the network complexity is increased and the spatial dispersion of the nodes tends to ease, but the average travel time and transfer rate continues to rise up, leading to the decreasing of the network transmission efficiency and the scattering of the nodes, (3) a good fault tolerance of the overall metro network of Guangzhou is revealed, but the spatial variance is observed, (4) the peak of degree centrality (DC) of the nodes is gradually moving northward along "Kecun Station–Guangzhou railway station–Jiahe Wanggang station", while the peak of betweenness centrality (BC) is changing from "Kecun station" to "Jiahe Wanggang station", and Jiahe Wanggang station has evolved into the most critical node in the current metro network of Guangzhou. In conclusion, this study should provide the scientific basis and significant decision-making support to the planning and operation management of GMN.

Keywords: metro network; complex network; topological structure; statistical analysis; GIS

1. Introduction

With the development of modern transportation technology, the emerging countries and their major cities all over the world are seeking a well-developed urban rail transit network system to alleviate the increasingly serious traffic problems, especially to optimize land use spatial structure and transport accessibility in the urban system [1–3]. In China, for example, since the city of Beijing became the first city to have a metro line in 1969, there are now 35 metropolises with a metro network with a total mileage of nearly 4600 km. Among them, the top three metropolises with the largest metro network mileage are Shanghai, Beijing, and Guangzhou. Since 1997, the Guangzhou Metro Network (GMN) has been developing rapidly, while the economy of the city has been booming continuously. Currently, the metro network system in Guangzhou is composed of 16 lines (service routes) and 218 stations. As an important part of the modern public transport service system, the urban metro network has many advantages, such as large traffic volume, high speed, long distance, less pollution, and intensive land use, compared with the conventional public transport modes, such as bus and tram. Certainly, achieving a reliable metro network structure and reasonable spatial network distribution pattern should play a significant role in improving the quality of urban public transport services and promoting the urban sustainable development, especially in a developing country context [4].

With the development of network science theory in the field of transport study, the complex network theory has become an important tool for modeling and characterizing the transport network topology. In the context of complex network theory [5,6], more and more scholars build transport network models based on Space-L and Space-P by using the entities (such as stops) of a complex network system and the interaction or association between the entities (such as service routes). Moreover, the graph theory and statistical physics are applied to explore the statistical law of the geometric and topological property in a transport network [7–10], with an important aim of providing the scientific references and decision-making support to the transport network planning. At present, the complex network theory has evolved into a new and extensive scientific paradigm of network system analysis and design. Many studies have focused on the analysis of the complexity, characteristics, and topological properties of urban rail transit network, such as a metro network, mainly considering the following aspects: (1) Measuring and characterizing the statistical characteristics such as node degree distribution of an urban metro network, and verifying its "small world" or/and "scale-free" phenomenon [11–13], (2) according to the geographical spatial characteristics of a given urban rail transit network, the powerful spatial analysis tools, such as geography information system (GIS), are integrated into the complex network analysis to evaluate the spatial network topological structure [14,15], (3) through measuring and quantifying the key topological parameters, such as degree centrality (DC), betweenness centrality (BC), and clustering coefficient (CC), the statistical characteristics of nodes in network are assessed thoroughly [16–21], (4) discussing the dynamic characteristics or the emergence behavior of the whole metro network while it is changing (such as being attacked), including vulnerability, reliability, robustness, etc. [22–27], furthermore, implementing the comparison between the urban metro network complexity characteristics in different cities, and then investigating the topology and classification of the given networks [19,21,28,29]. In summary, the existing research has carried out a more in-depth study of the topology and complexity characteristics of the transportation network. Especially, under the support of GIS, which is one of the innovative approaches that characterize the spatial correlation between spatial entities [30,31], the complex network analysis for the spatial topological characteristics of the transportation network shows a more extensive prospect.

However, the empirical analysis of the topology evolution of a given metro network in its complete growing period is less involved, making it difficult to recognize the characteristics and issues in each developmental stage during the growth of a network. In addition, as a typical real-life network, although the basic topological properties and characteristics of an urban metro network can be intuitively revealed through the complex network analysis, in the absence of time, distance, time of transfer or other network service information, it is hard to learn clearly about the performance of network service, especially under a specific topological structure. Indeed, for urban planners, how to improve the service level and quality of a transport network is a crucial issue in urban planning.

Therefore, on the basis of the complex network theory, this paper introduces the time cost, time of transfer, and other information of the travel paths among metro stations, and then establishes origin–destination (OD) matrixes and weighted network models during the growth of the Guangzhou Metro Network. Based on the complexity analysis of GMN, furthermore, this paper focuses on evaluating and characterizing the evolution of the spatial network topology and related issues in different network development stages by integrating with GIS. This study would serve as the scientific basis and decision-making support for the planning and operation management of the Guangzhou Metro Network.

2. Methodology

2.1. Modeling of Urban Metro Network

In the context of the network science theory, the modeling of an urban public transport network (such as a metro network) is generally implemented by using the methods of Space-L and Space-P. In the network modeling based on Space-L, a station is identified as one node in a network, while there is at least one service route (i.e., a metro line) between two adjacent nodes, these two nodes should be connected with an edge. As a network modeling of Space-P, a station is also defined as one node in a network, if there is at least one direct route (without transfer) between any two nodes, there is an edge between them. As shown in Figure 1, the actual shape of a public transport network is illustrated, and the corresponding network modeling based on Space-L and Space-P is also presented, respectively. Obviously, the Space-P network model is built on the service routes of a public transport network, and currently is widely applied to investigate the transportability between two nodes in a network. Therefore, compared with the Space-L model, the network structure modeling based on Space-P can more realistically reflect the service level and quality of an urban public transport network.

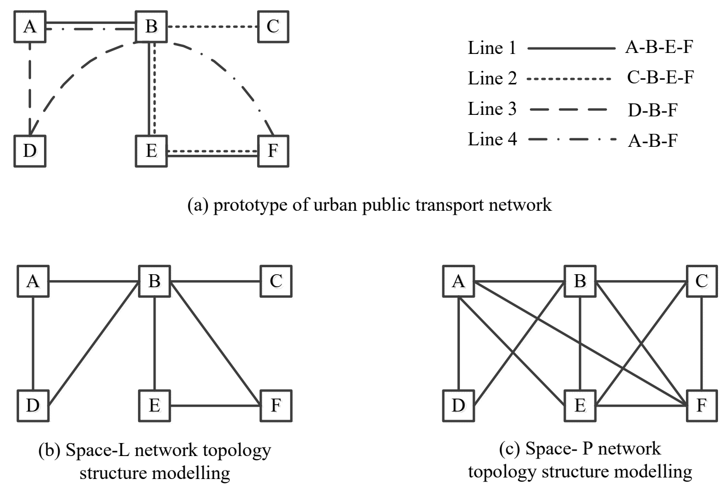


Figure 1. Public transport network modeling based on Space-L and Space-P.

A large number of studies have illustrated that complex network analysis is an efficient and convenient way to understand the topology of a public transport network. Nevertheless, due to the lack of the locations (geographical characteristics) of stations, and particularly the impedance information, such as travel time or time of transfer between stations, the outcome derived from the analysis cannot identify the service level and quality of a public transport network under its specific topological structure. According to a questionnaire survey on the residents' travel behavior by using metro mode in Guangzhou made by our research team in 2018, the residents in Guangzhou are most concerned with the convenience of travel by using metro mode, which specifically implies their psychological choice of less travel time and time of route change (i.e., transfer). It needs to be emphasized that the concerns of shorter time of transfer are also based on the priority choice of less travel time. From the residents' perspective, 30 min (without transfer) to travel by metro is the most ideal time cost, and the acceptable time cost is 30 to 50 min (or/and one time of transfer), but more than 50 min or/and over two times of transfer are the most unacceptable choice. Therefore, in order to attain the time cost and time of transfer required to travel between two stations in GMN, the spatial data modeling and analysis tool of GIS, i.e., ArcGIS 10.2 is applied. In the environment of GIS, the shortest path algorithm of Dijkstra is used to analyze the shortest path of travel time, and the path's time of transfer and length between any two nodes. Therefore, an origin–destination (OD) matrix can be accomplished on the basis of a given quantity of OD, such as travel time or time of transfer. If the total number of nodes is N in a network, it implies that there are N × N pairs of nodes. Therefore, the OD matrix (named time matrix) based on the minimum travel time of each pair of nodes can be built, and represented by:

$$\text{Time Matrix} = [t_{ij}]_{N\times N} \tag{1}$$

In the OD matrix, t_{ij} is the time cost of the shortest travel path between nodes i and j, when i = j, $t_{ij} = 0$, that is, the travel time between nodes i and i is excluded. The time cost for waiting and transferring during the travel between nodes i and j is not included in t_{ij}, as it is difficult to be gotten. Moreover, the OD matrix (name as transfer matrix) based on the time of transfer of each pair of nodes can be attained and identified as:

$$\text{Transfer Matrix} = [r_{ij}]_{N\times N} \tag{2}$$

r_{ij} is the times of transfer (route change) between nodes i and j, if i = j, $r_{ij} = 0$. In terms of the transfer matrix, the average time of transfer of all paths between any i * 0028 two nodes in the network can be calculated and represented as θ as follows.

$$\theta = \frac{\sum_{i=1,j=1}^{N} r_{ij}}{NP} \tag{3}$$

NP is the total number of the paths among the nodes in network.

Furthermore, the ratio of the number of paths which need to transfer to the total number of all paths in the network can be attained, and described as δ.

$$\delta = \frac{\rho}{NP} \tag{4}$$

ρ is the number of the paths with the time of transfer is more than 0.

In the Space-P network model, the edge between nodes i and j shows that there is at least one direct route (metro line) between two nodes. This implies that the time of transfer is 0 for each edge in the network. In this paper, however, through assigning the travel time to each edge and considering that the round-trip time is the same for each edge, an undirected weighted network model based on Space-P is constructed. As shown in Figure 2, each metro station is defined by a node in GMN. GMN can be represented as v, v ∈ V and V is the vertex set. While two metro stations are connected by a metro line (without transfer), there is an edge between them, and represented as s, s ∈ S, S is the edge set. As a result, the Guangzhou Metro Network can be described as G = (v,s), and the total number of nodes and edges is represented as N and M, respectively.

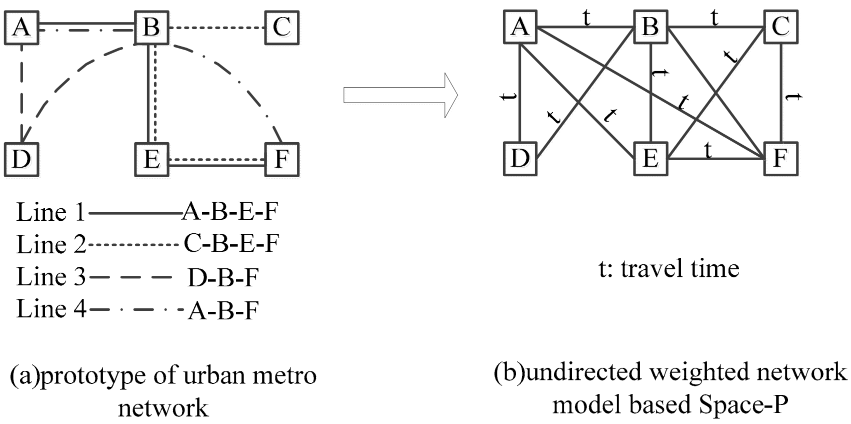


Figure 2. Undirected weighted network model based on Space-P.

2.2. Topology Measuring of the Overall Network

The indexes for evaluating the connectivity of the overall network include network diameter (T), average path length (L), network efficiency (E), connection rate (β), loop index (μ), actual loop forming rate (α), and actual combination degree (γ). Among these indexes, network diameter (T) is a key index to characterize the size of the network in space, while the average path length (L) reflects the spatial dispersion of nodes in the network. T and L can be calculated as follows:

$$T = \underset{i,j}{MAX}\{t_{ij}\} \tag{5}$$

$$L = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} t_{ij} \tag{6}$$

t_{ij} is the time cost of the shortest travel path between nodes i and j, where the maximum is the network diameter. N is the total number of nodes. In addition, the average of the reciprocal sum of t_{ij} is the network efficiency (E):

$$E = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{t_{ij}} \tag{7}$$

Network efficiency (E) aims to present the average proximity of nodes in an overall network. The larger the value of L of the network, the smaller the value of E, implying that the transmission efficiency of the network is lower, and the passenger flow in the network is more difficult to flow. Therefore, network efficiency (E) can be used to measure the anti-attack and robustness of the network.

The indicators of β and μ are used to measure the level of connectivity of the network, while α and γ are to evaluate the development potential of the network. β refers to the average number of edges of nodes in the network, that is, the ratio of the total number of edges (M) to the total number of nodes (N), and can be expressed as $\beta = M/N$. $\beta < 1$ indicates that the given network is a tree network, while $\beta > 1$ shows that the network is a loop network. Furthermore, μ refers to the number of loops in a network, that is $\mu = M - N + q$. The larger the value, the more loops, and the more developed network. q is the number of subgraphs of a network. In an urban metro network, stations are defined as nodes, and a series of nodes form a metro line, so the nodes in the line are connected to each other to constitute a complete subgraph, and different lines form the entire network through the transfer nodes. Therefore, the number of metro lines is the number of subgraphs. α is the ratio of two times of μ to the possible maximum number of loops (i.e., $(N - 1) \times (N - 2)$) in a network. The index of α aims to reveal the actual looping level of the network, expressed as $\alpha = 2\mu/(N - 1)\ (N - 2) = (M - N + q)/(2N - 5q)$. The smaller the value of α, the lower the level of looping, and 1-α indicates the potential for looping. γ is identified by the ratio of the total number of edges (M) to the possible maximum number of edges $(3 \times (N - 2))$, which reflects the networking level of edges, i.e., $\gamma = M/3 \times (N - 2)$.

2.3. Statistical Characteristic Measuring of Node

The indicators that reflect the statistical characteristics of nodes in a network in the context of complex network theory include node degree (ND), clustering coefficient (CC), and betweenness centrality (BC). Among these indicators, the number of edges connected to node i is defined as the node degree, i.e., $k_i = \Sigma s_{ij}$ ($j = 1, 2, \ldots, N$). The greater degree denotes that the node with the higher degree centrality (DC), implying that the node is more important in a network. The ratio of the degree of any node to the total number of edges can obtain the distribution characteristics of ND, which is generally described by a degree distribution function, expressed as P (k). P (k) shows the probability of the degree of a node, which is arbitrarily selected in a network, is exactly k. For a given network, a histogram can be used to represent the distribution of ND. In addition, the average ND of a network (denoted as K) can be represented as follows:

$$K = \frac{1}{N} \sum_{i=1}^{N} k_i \tag{8}$$

The clustering coefficient describes the average coupling degree of a node. Assume that node i in a network has M_i edges connected to other nodes, that is, these M_i nodes are identified as the neighbor nodes of node i. There is a possible maximum number ($M_i(M_i - 1)/2$) of edges between these M_i neighbor nodes. Therefore, the ratio of M_i to $M_i(M_i - 1)/2$ is defined as the clustering coefficient of the given node, that is:

$$C_i = \frac{2M_i}{M_i(M_i - 1)} \tag{9}$$

Moreover, the average clustering coefficient of the network can be calculated as follows:

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{10}$$

Obviously, the value of C ranges from 0 to 1. While C = 0, all nodes are isolated in the network, that is, there are no edges. When C = 1, it means that any two nodes in the network are connected with edges, that is, the network is a globally coupled network.

As mentioned above, the greater the degree of centrality of a node, the more important the node is in a network. However, there are often some nodes with low node centrality in a real-life network, which are very significant in a network. For example, in the urban metro network, although the degrees of some nodes are very small, they may be connecting nodes between lines, if such nodes were removed from the network, the related lines would be interrupted. Therefore, the nodes with lower degree centrality (NC) play a key role in the connectivity of network. For such a node, another global geometric quantity needs to be defined as a measure of its importance, that is, the betweenness centrality. In this paper, the betweenness of a node is denoted as B_i, which refers to the ratio of the number of shortest travel time paths which pass through node i to the total number of paths in network. Indeed, the value of B_i ranges from 0 to 1. The larger the value of B_i, the higher the betweenness centrality of node i, that is, the greater the influence of the node in a network. The formula for calculating the value of B_i is as follows:

$$B_i = \sum_{m,n} \frac{p_{mn}(i)}{p_{mn}} \, m, \; n \neq i, \; m \neq n \tag{11}$$

In the formula, p_{mn} (i) is the number of shortest travel time path which passes through node i, and p_{mn} is the total number of shortest time paths in a network.

3. Results and Analysis

3.1. Guangzhou Metro Network and Development

Since the first metro line (i.e., Line 1) was opened in 1999 in the city of Guangzhou, the Guangzhou Metro Network has developed rapidly in the past 20 years. As shown in Figure 3, the spatial evolution of GMN is a process of expanding outwards with the urban central area, including the districts of Yuexiu, Tianhe, Liwan, and Haizhu. With the increasing of network density in the urban central areas, GMN expands service coverage outward. Furthermore, Figure 4 shows the growth of the Guangzhou Metro Network (GMN) from 1999 to 2018. It can be seen that the development of the network in the early period (1999–2005) was relatively slow. By 2006, the mileage and the number of stations began to rise rapidly, for example, the network mileage increased from 58.5 to 116 km. By 2018, the network mileage jumped to 478 km, with 16 lines and 218 stations (see Figure 5).

The rapid development of the urban rail transit network has had a profound impact on the urban mobility pattern of Guangzhou. By the end of 2018, the proportion of residents' motorized trips reached 61% in public transport in the central urban areas of Guangzhou. Moreover, the daily average passenger volume of public transport modes including metro and bus has reached 16.49 million person-times in 2018, among which the daily average passenger volume of metro mode is more than eight million person-times and the intensity of daily average passenger flow has reached

2.19 million person-times of each kilometer, which is higher than that of Beijing (1.79), Shanghai (1.60). Figure 6 shows the evolution and comparison of the daily average passenger volumes of metro and bus in Guangzhou from 1999 to 2018. Obviously, with the development of GMN, the daily passenger volume of the metro is increasing rapidly, especially in 2016, it exceeded that of the bus, which has shown a decline since 2016.

Figure 3. Spatial structural evolution of the Guangzhou Metro Network.

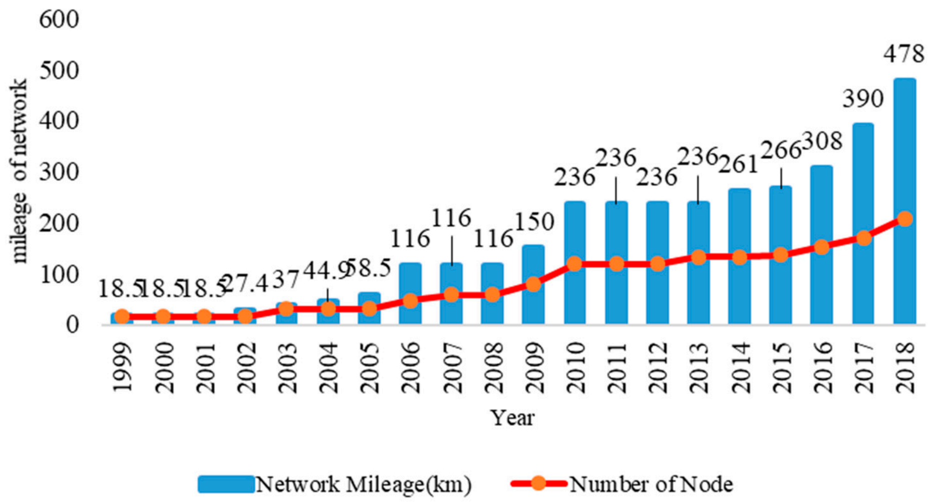


Figure 4. Development of the Guangzhou Metro Network (data source: The annual report of social and economic statistics of Guangzhou in 1999–2018).

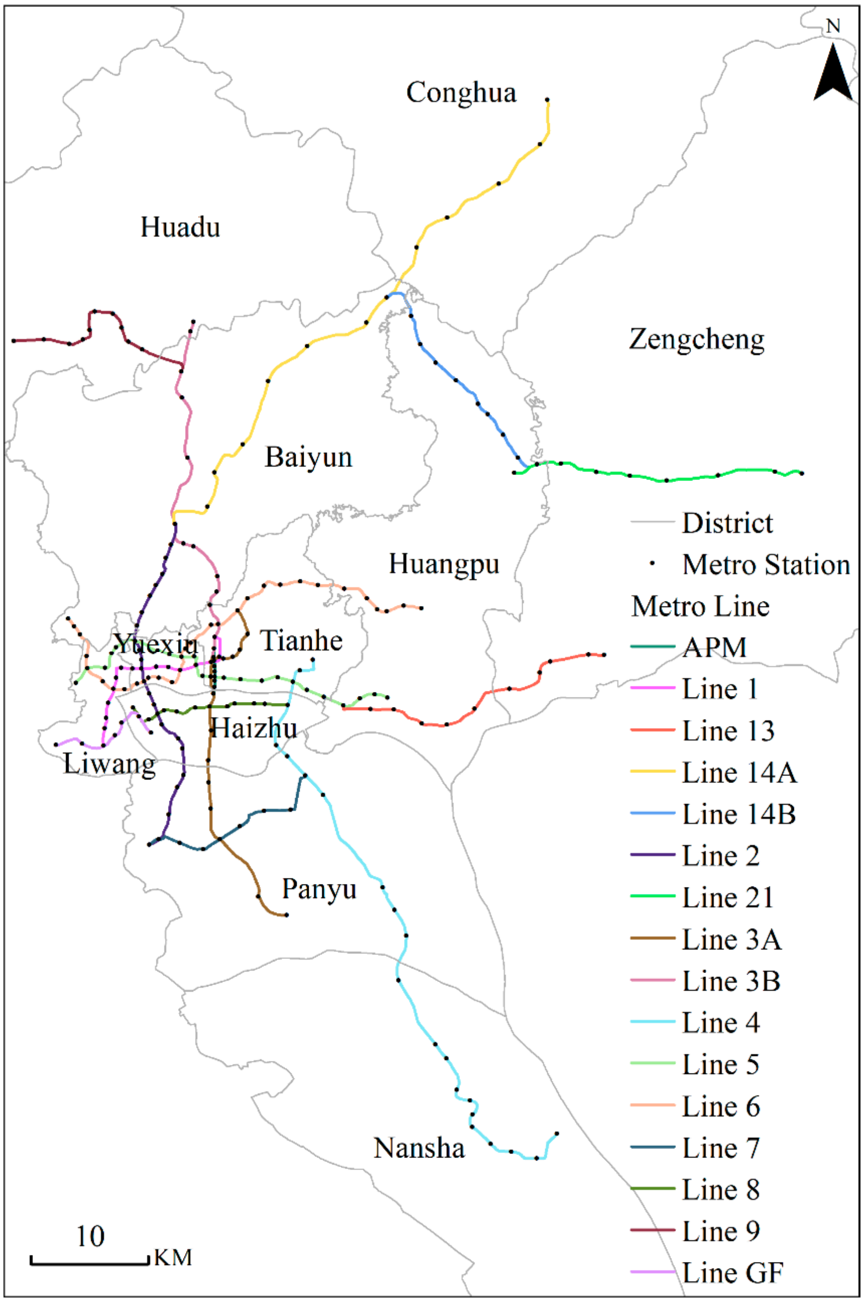


Figure 5. The Guangzhou Metro Network in 2018.

As the construction of a metro line often takes several years to complete, the growth of GMN shows a step-by-step phenomenon in 1999 to 2018 (see Figure 4). During the growing of the network, there was no or only one new metro line opened in some years, leading to a weak influence on the size and structure of the network, on the other hand, it should be emphasized that in some key years, several new metro lines were opened, causing a significant change in the network size and structure. Therefore, the study of this paper focuses on the network data analysis in the key time points (years), including the years of 1999, 2003, 2006, 2007, 2009, 2010, 2013, 2015, 2016, 2017, and 2018.

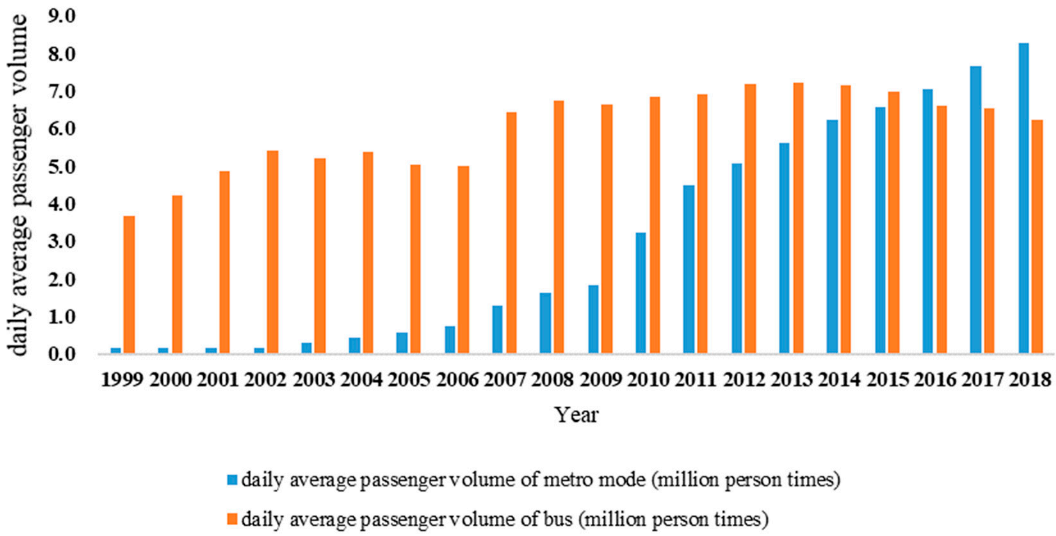


Figure 6. Evolution of daily average passenger volumes of metro and bus from 1999–2018 (data source: The annual report of social and economic statistics of Guangzhou in 1999–2018).

3.2. Evaluation and Characterization of the Topology of GMN

In terms of the metro network models based on Space-P in the key years, including 1999, 2003, 2006, 2007, 2009, 2010, 2013, 2015, 2016, 2017, and 2018, Figure 7 illustrates that the number of edges increased rapidly with the augmenting of the number of nodes from 1999 to 2018. Moreover, the number of edges increases much faster than that of nodes. This exhibited a phenomenon of super-linear growth of links in a complex network. Particularly, it is further observed that the number of edges increased linearly with that of nodes (R^2 = 0.9952) (see Figure 8). This shows that there is a large number of nodes with low DC and a small number of nodes with high DC (i.e., HUB nodes), implying that the Guangzhou Metro Network has an effect on the small-world network.

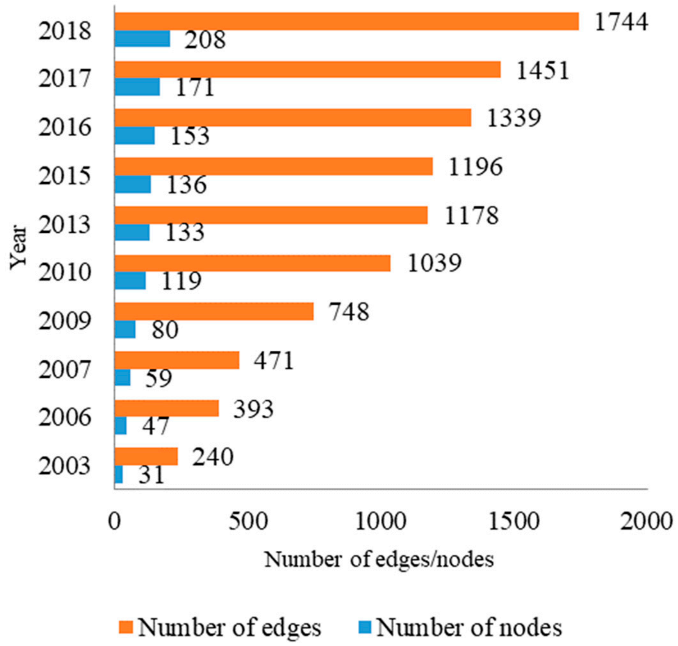


Figure 7. Growth of nodes and edges in the Guangzhou Metro Network.

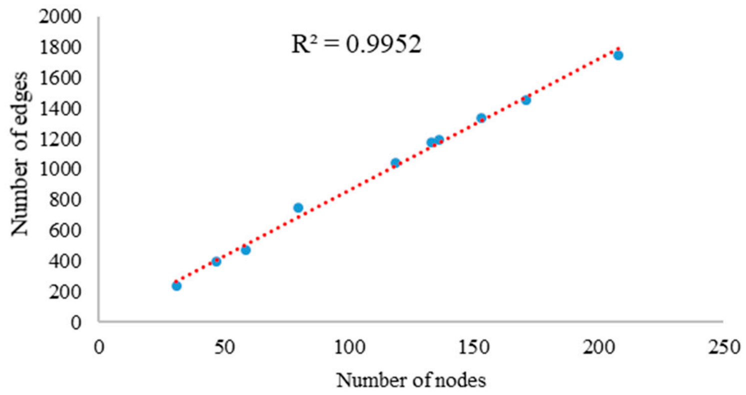


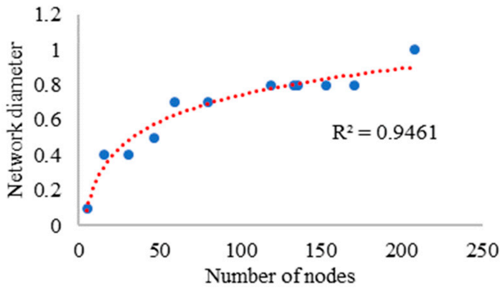
Figure 8. Linear growth relationship between node number and edge number.

As shown in Table 1, with the augmenting of network mileage, the network diameter (T) and average path length (L) also increase. The values of network diameter did not rise sharply but remained at 0.7–0.8 h from 2007 to 2017. This indicates that during this period, the Guangzhou Metro Network aimed to develop and improve the internal network instead of expanding outward. With the opening of metro lines 14 and 21, which expanded to the north in 2018, the network diameter increased to 1 h. In addition, the average path length is much smaller than the network diameter, and it increases more slowly than the network diameter. This further illustrates that GMN meets the basic characteristics of a small-world network. As shown in Figure 9, the network diameter and average path length increase logarithmically with the augmented network size (i.e., number of nodes) (the values of R^2 are 0.9461 and 0.8638, respectively). It means that while the complexity of GMN increases, the spatial dispersion of the nodes in the network will tend to ease. However, the network efficiency (E) exhibits a downward trend, reflecting that as the network expands, the average travel time in the network is continuously increasing, and the connectivity and accessibility of the overall network are gradually deteriorating.

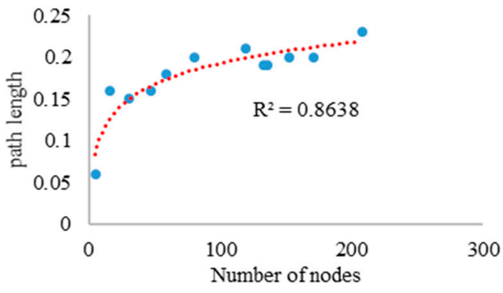
Table 1. Metrics of topological structure of the Guangzhou Metro Network.

Year	Mileage (KM)	T (Hour)	L (Hour)	E	β	μ	α	γ
1999	18.19	0.4	0.16	0.28	7.5	105	1	2.86
2003	35.57	0.4	0.15	0.28	7.74	211	0.49	2.76
2006	71.68	0.5	0.16	0.25	8.36	349	0.34	2.91
2007	112.56	0.7	0.18	0.23	7.98	416	0.25	2.75
2009	146.18	0.7	0.2	0.21	9.35	673	0.22	3.20
2010	213.77	0.8	0.21	0.23	9.18	983	0.14	3.11
2013	237.87	0.8	0.19	0.25	8.86	1055	0.12	3.00
2015	244.22	0.8	0.19	0.25	8.79	1070	0.12	2.98
2016	278.25	0.8	0.2	0.24	8.87	1199	0.11	3.00
2017	323.16	0.8	0.2	0.24	8.49	1293	0.09	2.86
2018	436.8	1	0.23	0.22	8.38	1552	0.07	2.82

In addition, Table 1 shows that t as a real-life network, the urban metro network is a typical loop network, and its connection rate (β) is always greater than 1. With the growth of GMN, there are more opportunities for convergence between lines. This leads to a significant increase of the loop index (μ), and a more developed network. However, both the actual loop rate (α) and the actual combination degree (γ) of GMN are gradually decreasing. Obviously, combining the characteristic of gradually decreasing the network efficiency (E), it can explain that with the growth of GMN, the proximity between nodes in the network is declining.



(**a**) Network diameter (D)



(**b**) Average path length (L)

Figure 9. Logarithmic growth of network diameter, average path length and network size.

The probability distribution of ND of GMN in each key year illustrates the phenomenon of long tail (see Figure 10), and the evolution can be divided into three stages (since there was only one metro line in 1999, the data from this year were removed): (1) The probability distribution of ND from 2003 to 2006 was a typical power-law distribution, indicating the apparent small-world characteristics (see Figure 10i,j), (2) during 2007–2013, with the growth of the network, the probability distribution of ND did not have power-law distribution characteristics, but tended to be a Poisson distribution, showing the characteristics of a scale-free network, (3) in 2015–2018, the probability distribution of ND had more obvious characteristics of power law, illustrating the effect of a small-world network.

Table 2 shows the average node degree (K), the average clustering coefficient (C), the average time of transfer (θ), and transfer rate (δ) of GMN in each key year. The results show that in the process of network growth, there is a large average node degree. Furthermore, the values of the average clustering coefficient (C) have been at a high level, illustrating that the metro network in Guangzhou has better fault tolerance, i.e., the alternatives of the path are strong. In particular, the network in 1999 had only one line, so the nodes in the network were connected two by two, and the value of the average clustering coefficient (C) was 1. At this time, the network was a globally coupled network. With the increase in the number of lines and stations, the average clustering coefficient (C) decreased slightly, but the trend of clustering has remained overall.

Table 2. Statistical characteristics of the topology of the Guangzhou Metro Network.

Year	K	C	θ	δ
1999	15.00	1.00	0	0
2003	15.48	0.98	0.48	0.48
2006	16.72	0.96	0.77	0.64
2007	15.97	0.96	1.06	0.72
2009	18.70	0.94	1.22	0.76
2010	18.37	0.94	1.68	0.84
2013	17.48	0.89	1.94	0.87
2015	17.36	0.89	1.90	0.87
2016	17.53	0.89	2.03	0.88
2017	16.79	0.90	2.25	0.90
2018	16.62	0.91	2.55	0.92

Furthermore, as shown in Table 2, the average time of transfer (θ) and the average transfer rate (δ) of GMN increase with the growth of the network, particularly the increase of the value ofθhas a linear relationship with the increasing of the number of nodes (R^2 = 0.982) (see Figure 11). Moreover, Table 2 shows that the value of δ reached 92% in 2018, which means that 92 of the 100 shortest travel time paths needed to be transferred, and more than two times of transfer were required on average. Obviously, in terms of the characteristics of the gradual decline of α, γ, and E, it further reveals that the larger size of the network, the more dispersed the nodes, finally leading to the more difficult transmission of passenger flows in the network.

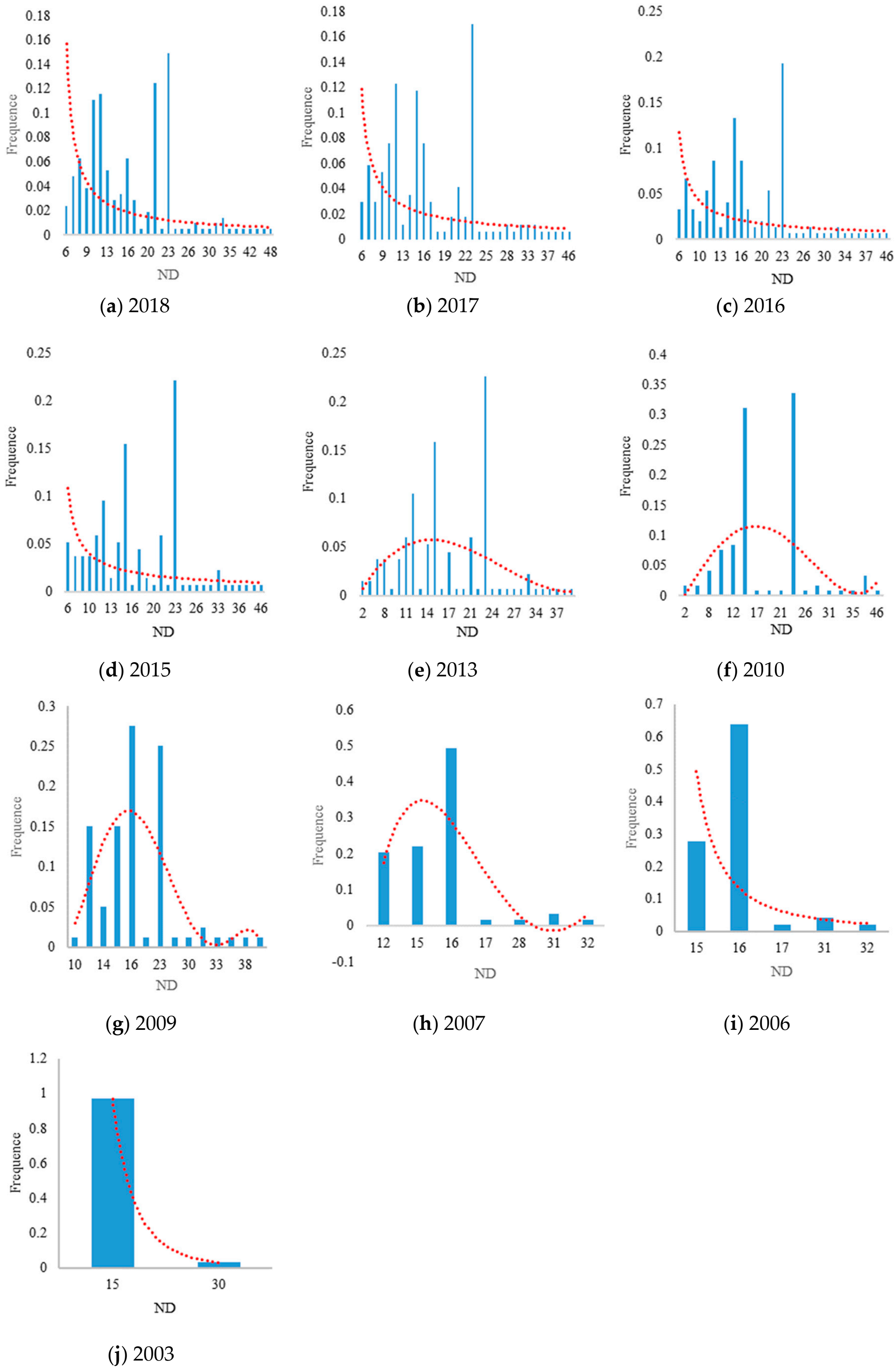


Figure 10. Evolution of node degree probability distribution.

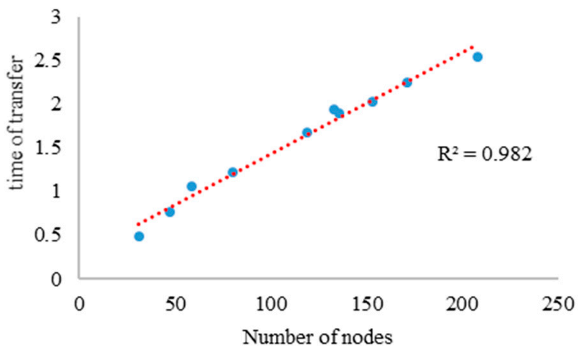


Figure 11. Linear growth relationship between average transfer times and network size.

3.3. Network Topology Spatial Analysis Based on GIS

In the environment of ArcGIS 10.2, the degree centrality (DC) and betweenness centrality (BC) of the nodes in GMN in the key years of 2006, 2010, 2015, and 2018 were graded by using the method of natural breakpoint, and then the method of natural neighbor was applied to interpolate the values of DC and BC of each node to generate a trend surface (see Figure 12).

As shown in Figure 12, most transfer nodes where two or more lines meet have a high DC, and if a metro line has more nodes (stations) and transfer nodes, the DC of its nodes becomes greater. According to the spatial and temporal evolution of DC in GMN, the center of the network is gradually moving north along the "Kecun Station–Guangzhou Railway Station–Jiahe Wanggang Station". Particularly, the DC of transfer nodes in GMN was significantly higher than other nodes in 2006. Therefore, a degree-centrality peak was formed at the positions of the transfer nodes, and the highest peak was "Kecun Station" in 2006. In 2010 and 2015, the DC of nodes in GMN formed two peak lines, namely Line 2 running from north to south and Line 5 running from east to west, and they meet at "Guangzhou Railway Station". Therefore, the position of Guangzhou Railway Station was the highest peak of DC in 2010 and 2015. In 2018, a new peak line was raised along Line 4 (running from north to south), furthermore, the DC of nodes located in the southern region has been improved obviously. The reason is that the opening of Line 7 in 2018 extends to the south to connect the lines of 2, 3 and 4, which finally are connected with each other. Compared with the southern region, the DC of the nodes located in the north is lower because of their relatively high spatial dispersion. This also results in poor network fault tolerance in the northern region.

In Figure 12, the betweenness centrality (BC) hierarchical distributions of the nodes in the Guangzhou metro network in the years of 2006, 2010, 2015, and 2018 is also illustrated. In terms of the spatial and temporal evolution of the betweenness centrality (BC) in GMN, the center of the network is directly changed from "Kecun Station" to "Jiahe Wanggang Station". Unlike the distribution of node degree, nodes with larger betweenness are not just transfer nodes, some nodes with smaller DC have high BC. This implies that such nodes are also significant for the connectivity between the lines. The BC of nodes in GMN all took "Kukura Station" as the highest peak in 2006, 2010, and 2015. Importantly, the network in 2010 and 2015 had two peak lines of BC, one running along Line 8 and east to "Changang Station" to connect to Line 2, and the other running west to "Wanshengwei Station" to connect to Line 4, as the center of "Kecun Station". It means that the nodes on the peak lines are significant for the connectivity of the network. In 2018, the BC of nodes located in the northern region was significantly higher than that in other areas, moreover, the highest peak changed from "Kecun Station" to "Jiahe Wanggang Station". Furthermore, with "Jiahe Wanggang Station" as the center, one peak line went north to "Xinhe Station" along Line 14 and the other peak line south to "Kecun Station" along Line 3. It is clear that Jiahe Wanggang Station has evolved into the most critical node in GMN. If the node was blocked, the lines in the northern region would be disconnected from the whole network.

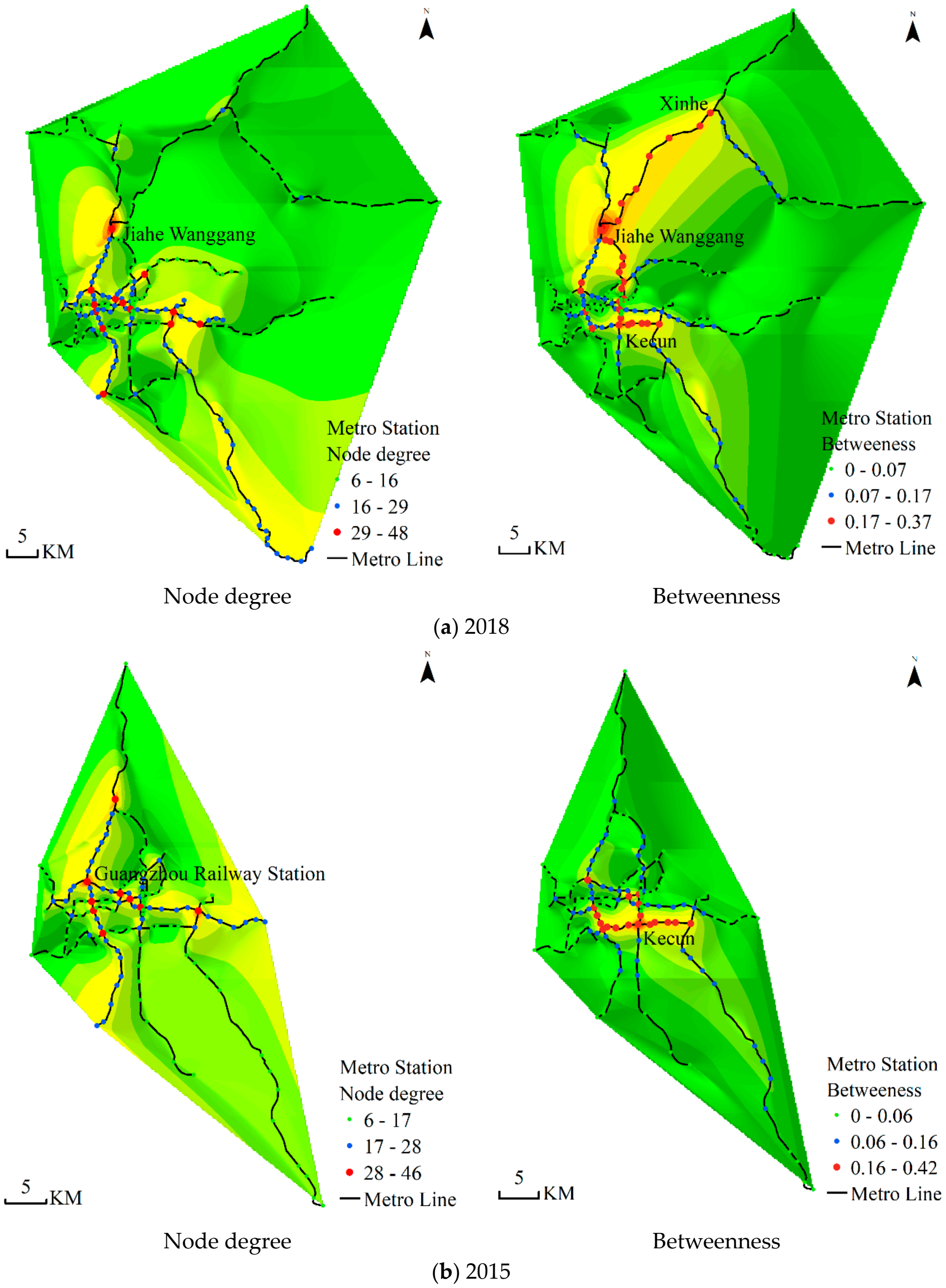


Figure 12. *Cont.*

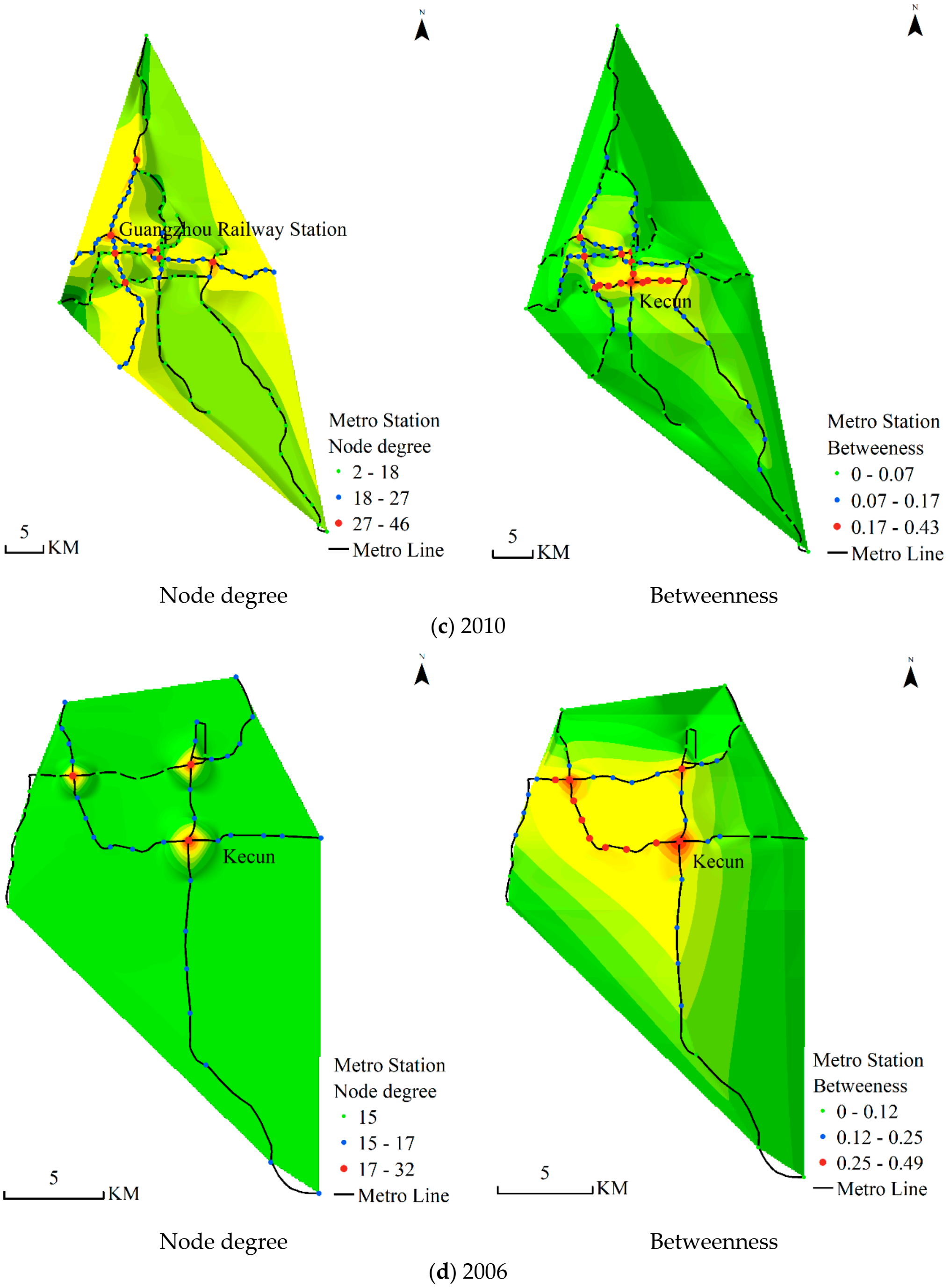


Figure 12. Spatio-temporal evolution of degree centrality and betweenness centrality in the Guangzhou Metro Network.

4. Conclusions

This paper takes the city of Guangzhou as the study area and uses the complex network theory to construct the OD matrixes of the Guangzhou Metro Network in the key years from 1999 to 2018, and the corresponding undirected weighted network models based on Space-P are achieved. And thus, the paper focuses on the evolution and evaluation of the topological properties and characteristics of the metro network of Guangzhou with the integration of geographic information system (GIS). The aim of the paper is to provide a scientific basis and decision support for the metro network planning and operation management in Guangzhou. The results derived from this study can be concluded in the following. Firstly, the metro network of Guangzhou illustrates the basic characteristics of a small-world network. In the network, there is a large number of nodes with low degree centrality and a small number of nodes with high degree centrality (i.e., HUB nodes). Moreover, the average path length of the network is much smaller than the network diameter, specifically, it increases more slowly than the network diameter of the network. Secondly, with the growth of the metro network in Guangzhou, while the complexity of the network increases, the spatial dispersion of internal nodes tends to ease. Nevertheless, a large number of nodes spread outward, leading to an increase in the average travel time and the average transfer rate of the network, leading to the decreasing of the network efficiency. Thirdly, the connectivity indexes of α and γ in GMN are gradually decreasing, and the average time of transfer increases linearly with the growth of network. Combining with the gradually decreasing characteristics of the network efficiency, it reveals that the nodes in the network become more dispersed with the growth of the network, and the transmission of passenger flow in the network becomes more difficult. Fourthly, a higher average clustering coefficient and a larger average node degree indicate that the metro network in Guangzhou has better overall fault tolerance, i.e., there are more routes to choose from among the nodes. However, there are spatial differences, particularly the paths to or from the northern region are relatively poor in substitution. Finally, based on the evolution of the degree centrality of nodes, the center of the metro network in Guangzhou is gradually moving north along "Kecun Station–Guangzhou Railway Station–Jiahe Wanggang Station", but from the evolution of the betweenness centrality of nodes, the metro network center is directly changed from "Kecun Station" to "Jiahe Wanggang Station". Jiahe Wanggang Station has evolved into the most critical node in the current network. If the node is blocked, all lines in the northern region will be disconnected from the whole network.

The above results mentioned in this paper should provide important reference information and decision support for urban planners or metro operation managers of the city of Guangzhou, including what are the topology properties and characteristics of the metro network, how to measure the attack resistance and robustness of the metro network, and how to optimize and strengthen the equilibrium and induction of passenger flow in the metro network based on the importance of a node in the context of complex network analysis. The future work of this paper will further investigate and characterize the accessibility performance and existing issues of the metro network under the specific network topology, through the integration of accessibility measuring models and complex network analysis, and finally, provide theoretical basis and policy suggestions for the scientific planning and construction of the urban metro network in the city of Guangzhou.

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