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Construction and Characteristics Analysis of the Xi'an Public Transport Network Considering Single-Mode and Multi-Mode Transferring

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Abstract: The connectivity of the urban public transport network and the convenience of transfers between modes of transit are important factors that affect whether passengers choose public transport. Identifying the key nodes that affect network connectivity, direct access, transfers, and clarifying the main factors that restrict the network efficiency play important roles in improving the efficiency of the public transport network and establishing a "green city". On this premise, this paper constructs two single-layer networks and a composite network that can reflect the transfer relationship between 'bus–bus', 'metro–metro', and 'metro–bus' based on the method of Space-P. The composite network realizes the integration study of homogeneous and heterogeneous stops, lines, and transfer relationships in the public transport network. At the same time, five kinds of centrality indexes are applied to the transport transfer network, and the significance of these indexes in the network is explained. Through the comprehensive analysis of these five types of indexes, the key nodes affecting the network connectivity, direct access and transfer efficiency, can be identified more accurately. Taking the public transport network of Xi'an as an example, the structural characteristics of the networks, including scale-free and small-world characteristics, were empirically analyzed. The main stops that play important roles in networks were identified based on the integrated centrality, degrees, and weight degrees. The research results showed the following: (1) Xi'an's metro network, bus network, and metro–bus composite network all have scale-free and small-world characteristics. (2) The influence of the key stops of the metro network is concentrated, while the influence of the key stops of the bus network is scattered. (3) The public transport network in the first ring road area of Xi'an has the highest degree of direct access, and the core areas of the south, west, and north of Xi'an also have high direct access. However, the direct access in the area east of Xi'an is slightly lower. (4) Xi'an's bus transport network covers a large area, showing the characteristics of a dual-core "central + southern" network. (5) The metro–bus composite network demonstrates a closer connection between stops and a more balanced network. (6) Finally, the degree of direct access to stops in the bus transport network and metro transport network shows the characteristics of "the single core is dominant, and the circle diffusion weakens step by step".

Keywords: metro transport; bus transport; Space-P network; direct access

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1. Introduction

Economic development has led to a large influx of people into cities [1], and the rapid growth of both resident and transient populations [2] has resulted in many transport problems, such as transport congestion [3,4], environmental pollution [5,6], and increased transport accidents [7,8]. From the perspective of green development [9], it is particularly important to build an efficient urban public transport system to improve the above-mentioned urban transport problems and better meet the transport needs of the urban population [10]. However, the development of public transport systems in China's major cities still faces problems such as an uneven distribution of public transport routes, inconsistency between the distribution of public transport stops and residents' travel needs, and the poor accessibility of the public transport network [11]. Therefore, it is necessary to evaluate the efficiency of public transport systems and identify important factors constraining the system's efficient operation to improve its service efficiency [12]. Complex networks, as powerful tools for analyzing large complex systems, have been widely used in related fields of research on urban public transport systems in recent years [13,14] .

Different methods exist for constructing transport networks, such as Space-L and Space-P, and each method can evaluate the network from different angles [15,16]. The Space-L method is a topological mapping of the actual transport network [17,18], describing the original form of the real transport network. The Space-L method was used to abstract the local and national bus networks in the UK into an undirected network, and it was found that the distribution of the bus network exhibited a clear power-law decay trend [19]. Bus, metro, and public transport networks have been studied in multiple cities, such as Curitiba, Sao Paulo, and Seoul, and it was found that the small-world properties of the network were more obvious when there were a large number of intermediate stops [20]. Moreover, a network constructed based on the Space-P method emphasizes the transfer relationships between stops and can reflect the level of transfer service in the transport network [21]. Directed Space-L and directed Space-P models were proposed, and based on these two models, analyses of the characteristics of the node degree and path length of the Harbin bus network were conducted in [22]. It was found that under the directed Space-P model, the node degree and weighted degree of the Harbin bus network showed an exponential distribution pattern, and both degrees had a significant positive correlation [23]. The Jiaozuo city bus network was constructed by using the Space-P method, where the coupling coordination of nodes was clustered and analyzed based on township and kilometer grids as the basic spatial unit [24]. In recent years, scholars have carried out multi-layer transport network construction. Refs. [25–27] respectively constructed a metro–bus composite network based on the Space-L method and investigated the robustness of single-layer networks and composite networks. Based on this kind of research, Ref. [28] constructed a weighted Space-L metro–bus composite transport network with travel time as the weight, considering the running time and transfer time on board, and carried out key stop identification and robustness analysis. Ref. [29] constructed a Space-L directional weighted complex network for the metro and bus and classified the stops based on the passenger flow of the stops. From the above research, we can see that the network construction and problem analysis in the field of public transport have gradually developed from focusing on a single mode of transport to focusing on the comprehensive role of multiple modes of transport, and gradually transformed from an unweighted network to a weighted network that takes multiple factors into account, and these studies are more and more capable of reflecting the operation of the real network.

However, a variety of network integration is not a simple superposition. On the one hand, the location of each stop is different, taking different roles; on the other hand, the metro network and the bus network have heterogeneity, and the network characteristics caused by the collection or superposition of their respective networks are different. In addition, factors such as line density, transfer times between stops, transfer key nodes in the network, and overall network accessibility presented by single-layer network and multi-layer network need to be explored. The current research on the metro–bus complex network has the following two shortcomings. First, most of the existing research on single-layer and multi-layer transport networks are based on the Space-L method to build complex networks with geometric shapes similar to actual transport networks and study their topological structure, network toughness, etc. However, such networks can only reflect the connectivity of stops, but cannot reflect whether there is direct access between stops or whether there is a need for transfer to reach them. Second, the existing transport network modeling mostly homogenizes the heterogeneous characteristics and lacks the objective description of the attribute diversity and hierarchical structure difference of different transport modes in the actual transport network.

With the diversified development of urban public transport systems, the transfer level and the efficiency between bus, metro, light rail, and other modes of transport have become important factors affecting traveler experience. Therefore, it is particularly important to identify the important nodes of the network including the transfer relationship, explore the constraints of bus–bus transfer, metro–metro transfer, and metro–bus transfer, and evaluate the network characteristics after the superposition of multiple public transport modes. Based on this, this paper uses the Space-P method to build a composite urban bus and metro network, integrating stops (bus and metro stops), lines (bus and metro lines), and transfer relationships (bus–bus transfer, metro–metro transfer, and metro–bus transfer) into a unified network. By analyzing and comparing the structural characteristics, connectivity, direct access, and direct line density of a single transport network and composite network, the network characteristics and main factors affecting the network efficiency are found, which can provide new research ideas and reference for the optimization of a public transport network.

This paper is organized as follows. First, the concepts of the multi-layer network and the public transport network model based on space-p are shown. Then, an example to carry on the empirical analysis is made in order to find the character of the public transport network structure. Finally, the research ideas and main conclusions of the paper are summarized and expounded.

2. Research Methods

2.1. Multi-Layer Network

Network science is a new interdisciplinary science specializing in the qualitative and quantitative laws of various topological properties and dynamic characteristics of complex networks [30]. Initially, network science was mainly based on specific research fields that built single-layer networks to analyze their topological structure characteristics and evaluate the efficiency and performance of network nodes (reliability, robustness, destruction resistance, etc.) [31]. As this research field deepened, scholars found that many systems in the real world have complex and highly interdependent structures, and single-layer networks are unable to address the problem of the cross-fusion of multiple systems; therefore, multi-layer network research gradually started attracting more and more attention [32,33]. Each layer in the multi-layer network represents a system or a subsystem, and the connection between the networks is realized based on the relationship between the actual system's layers [34,35]. Each layer in the multi-layer network may exhibit different local and global structural characteristics than those in the single-layer network, which provides an effective method for analyzing the interaction between different systems and the formation mechanism of the network [36–38].

2.2. Representation of a Multi-Layer Network of Urban Public Transport

The multi-layer network of urban public transport is expressed as $G^{\text{three}} = (G^U, G^L, G^O)$. The upper-layer network $G^{\text{U}} = (V^U, E^U, W^U)$ represents the bus network, the lower-layer network $G^L = (V^L, E^L, W^L)$ represents the urban rail transit network, and the intermediate coupling network $G^O = (V^O, E^O, W^O)$ represents the metro–bus transfer network. V is the node set of each network layer, expressed as $V = \{V_1, V_2, \ldots, V_n\}$; n represents the number of nodes in the network at this layer; E is the set of edges in the network in each layer, expressed as $E = \{e_{ij} = (v_i, v_j)\}$; and e_{ij} represents the edge connection between node v_i and v_j. In network G^O, V is the transfer stop between the metro and bus, and E is the connecting edge of the metro and bus transfer stop. Here, the number of bus lines between two stops is taken as the weight value, indicating the degree of connectivity between two stops in the network. $W = \{W_{ij}\}n * n$, $W_{ij} > 0$ indicates that there are connected edges between the starting and ending points v_i and v_j, and the weight is W_{ij}. $W_{ij} = 0$ indicates that v_i and v_j do not have connected edges. Based on whether the weight W_{ij} is 0, the adjacency matrix $A = \{a_{ij}\}n * n$ of the multi-layer network can be obtained:

$$a_{ij} = \begin{cases} 1, (v_i, v_j) \in E \\ 0, (v_i, v_j) \notin E \end{cases},$$

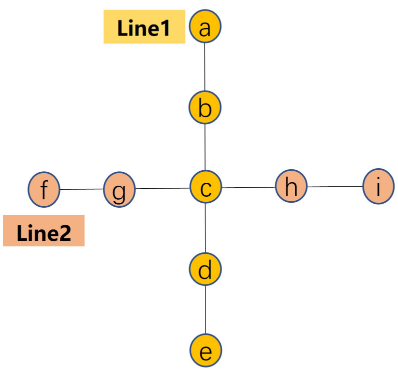
where an a_{ij} value of 1 means there is a connected edge between two points and an a_{ij} value of 0 means there is no connected edge between two points. At the same time, it should be noted that the network diagram is undirected, that is, if there are connected edges from v_i to v_j, a_{ij} and a_{ji} are both 1 in the adjacency matrix, indicating the same edge.

3. Model Construction

3.1. Adjacency Relationship Construction Based on Space-P

Space-L, Space-P, and other spatial models are commonly used in research on public transport networks. Among these models, Space-L is also known as the L-space model. In this model, the stops in the transport network are conceptualized as nodes. If two stops are adjacent to each other on the same line, these two stops will be connected. Space-P is also known as the P-space model. In this model, the stops in the transport network are also conceptualized as nodes. If two stops are on the same line, the two stops are connected. The biggest difference between the Space-P and Space-L models is that Space-P highlights transfer points, which can be visually observed through the network diagram. All directly connected points on the network belong to the same line. If any two points can be reached by more than two edges, this means that there is a transfer relationship between the two points. The conversion relationship between the number of edges connecting two points n and the number of transfers h is $h = n - 1$. In addition, according to the studies in [15,16], transfer has a great impact on passengers' travel efficiency and travel experience. Therefore, this paper uses Space-P to construct the transport network in order to better reveal the characteristics of the bus network from the perspective of the whole passenger travel process.

(1) Adjacency matrix: Adjacency is represented by the adjacency matrix. The adjacency matrix of the space-P transport network is shown in Figure 1. Figure 1a shows two metro lines, in which a, b, c, d, and e are stops on line 1 and f, g, c, h, and i are stops on line 2. The adjacency matrix constructed based on Space-P is shown in Figure 1b. The adjacency relation is 1 or 0.



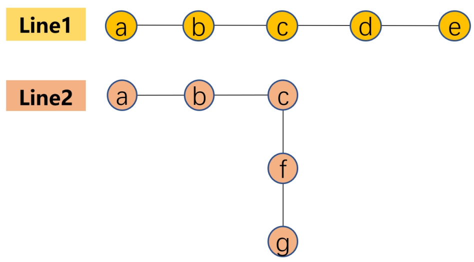
(a)

	a	b	c	d	e	f	g	h	i
a	0	1	1	1	1	0	0	0	0
b	1	0	1	1	1	0	0	0	0
c	1	1	0	1	1	1	1	1	1
d	1	1	1	0	1	0	0	0	0
e	1	1	1	1	0	0	0	0	0
f	0	0	1	0	0	0	1	1	1
g	0	0	1	0	0	1	0	1	1
h	0	0	1	0	0	1	1	0	1
i	0	0	1	0	0	1	1	1	0

(b)

Figure 1. Adjacency matrix. Adjacency matrix construction of transport lines. (**a**) Transport lines. There are two metro lines, in which a, b, c, d, and e are stops on line 1 and f, g, c, h, and i are stops on line 2. (**b**) The adjacency matrix. The adjacency matrix is constructed based on Space-P model.

(2) Weight matrix: In the weight matrix, the weight of the connected edge is the number of lines between two points. If there is only one line between two points, the weight of the connected edge between two points is 1; if there are n lines connecting two points, the weight of the connected edge is n. In Figure 2, two lines exist, Line 1 and Line 2. Line 1 passes through nodes a, b, c, d, and e and Line 2 passes through nodes a, b, c, f, and g, as shown in Figure 2a. The weight matrix formed by the two lines is shown in Figure 2b.



(a)

	a	b	c	d	e	f	g
a	0	2	2	1	1	1	1
b	2	0	2	1	1	1	1
c	2	2	0	1	1	1	1
d	1	1	1	0	1	0	0
e	1	1	1	1	0	0	0
f	1	1	1	0	0	0	1
g	1	1	1	0	0	1	0

(b)

Figure 2. Weight matrix. Weight matrix construction of transport lines. (**a**) Transport lines. There are two bus lines, in which Line 1 passes through nodes a, b, c, d, and e, and Line 2 passes through nodes a, b, c, f, and g. (**b**) The weight matrix. The weight between two points represents the number of transport lines connecting the two points.

3.2. Identification of Transfer Relationships in the Bus Network

The nodes of the bus network are the bus stops, and the connecting edges include two types of connecting edges. One type is the connecting edge between different stops on the same bus line, and the other one is the connecting edge between bus–bus transfer stops. A hypernode diagram is selected for the identification of transfer stops, and ArcGIS software is used to aggregate all bus stops. According to [18], the transfer distance between two bus stops is generally not more than 100 m, and thus, stops with a linear distance of less than 100 m are aggregated into a hypernode. Because the Space-P network is defined as having connected edges between stops on the same line, and not connecting edges between stops on different lines, as shown in Figure 3, a, b, and c, are bus stops whose linear distance from each other is less than 100 m. These three points are identified as the transfer stops of each bus line and are aggregated into hypernode d, which represents the transfer relationship between passengers on different bus lines in the real network.

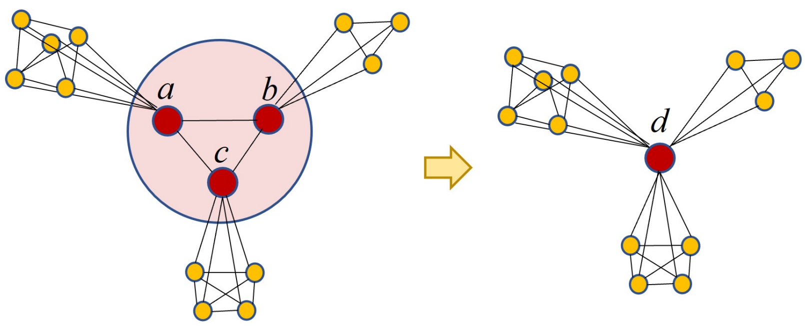


Figure 3. Transfer stop aggregation.

3.3. Identification of the Transfer Relationship in the Metro Network

The metro network is also built using Space-P, and the metro stops are considered nodes in the network. If the stops belong to the same line, there are connected edges between the stops; if the stops do not belong to the same line, there are no connected edges between the stops. The transfer relationship is represented by the number of edges between two points, as shown in Figure 4. Line 1 and line 2 are two metro lines forming independent communities. Stops on the same line have side connections, while stops on different lines have no direct side connections. There is a transfer stop between the two lines, and the transfer relationship can be determined by observing the number of connecting edges between the two nodes. The stops on lines 1 and 2 are connected by one transfer.

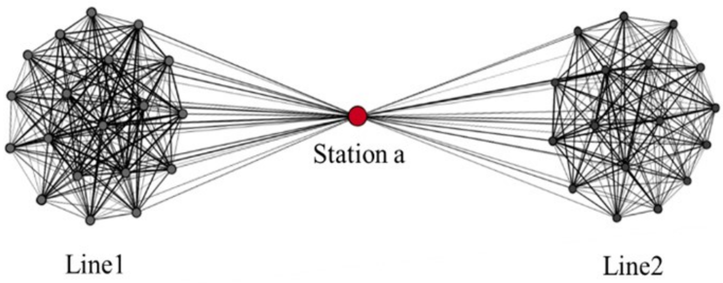


Figure 4. Metro transfer relationship.

3.4. Identification of Metro–Bus Transfer Relationship in Composite Metro–Bus Network

The metro network and the bus network are connected by transfers, as shown in Figure 5. Bus stops a, b, and c, located within 500 m of metro stop d on the metro network layer, are regarded as transferable bus stops. ArcGIS is used to identify the transfer stops and establish the metro–bus transfer edge. The waiting time and walking time involved in the transfer process between metro and bus are considered as the weight of the transfer edge when constructing the network. Metro-bus interchanges connect the metro network with the bus network. Within the city, there are several metro–bus transfer subnetworks, and these can be regarded as subnetworks coupling the metro and bus networks, as shown in Figure 5.

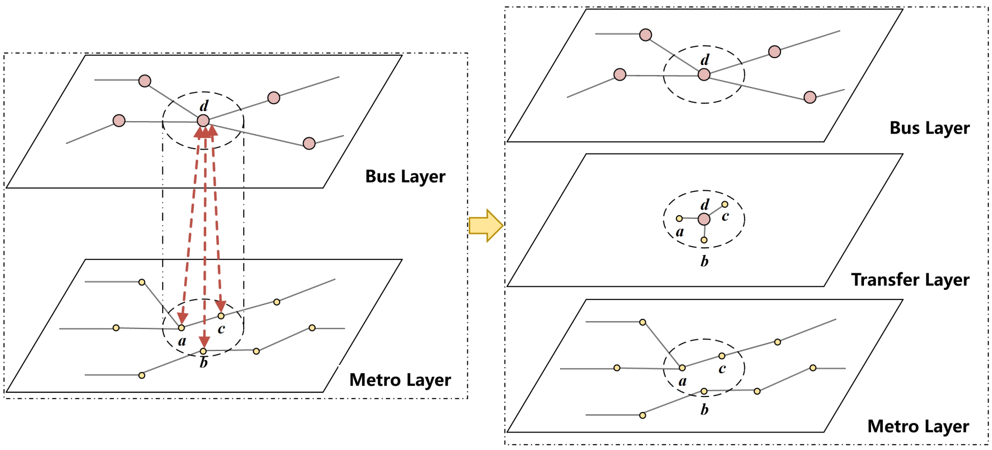


Figure 5. Identification of transfer relationships between metro network and bus network.

4. Network Topology Structure Indicators

4.1. Degrees and Degree Distribution in Space-P Transport Networks

When discussing individual nodes, the degree can describe the statistical properties of their connections and is an important and intuitive node attribute. The number of nodes connected to node i among other nodes is called the degree of node i, and its calculation method is shown in Equation (1):

$$k_i = \sum_j a_{ij} = \sum_j a_{ji} \tag{1}$$

Intuitively, a node will have more "influence" if it has more nodes connected to it. In a complex network, the network's average degree $\langle k \rangle$ is the average of all node degrees, and its calculation method is shown in Equation (2):

$$\langle k \rangle = \frac{1}{N} \sum_i a_{ij} = \frac{1}{N} \sum_i k_i \tag{2}$$

The distribution of degrees $p(k)$ is the probability of any node having a degree of k. In a regular network, the degree distribution is $Delta$ because the sequence of degrees is relatively simple. The degree distribution of a completely random network is similar to the Poisson distribution, which reaches its peak when the value is the average degree, because it is practically impossible for the degree value of one node to be much larger than the average degree, so the probability of the value being far away from the peak shows an exponentially declining trend. In recent years, a large number of studies have found that the degree distribution of many practical networks can be better represented by a power-law distribution, which, following most real-life complex networks, has a much slower rate of decline than that of the Poisson distribution. In the transport network based on the Space-P method, the degree value represents the number of stops that a stop can reach directly without transfer, which can reflect the accessibility of stops in the transport network.

4.2. Clustering Coefficient in Space-P Transport Networks

In a complex network, if the number of edges of node i is k_i, it means that there are k_i nodes adjacent to it. Theoretically, the maximum number of possible edges between these adjacent nodes is $k_i(k_i - 1)/2$, that is, the maximum number of connections that can be established between adjacent components in a complex system. The actual number of edges is only E_i, so the actual number of connections between adjacent components in a complex system is $E_i < k_i(k_i - 1)/2$. Therefore, the clustering coefficient C_i of node i can be defined as the ratio of E_i to k_i, as expressed in Equation (3):

$$C_i = 2E_i / k_i(k_i - 1) \tag{3}$$

In graph theory, the clustering coefficient can also represent the level of clustering between nodes. Combined with the geometric description of the graph, the formula of the clustering coefficient can be expressed as in Equation (4):

$$C_i = \frac{N_i}{T_{ri}} \tag{4}$$

where N_i refers to the number of closed three-point groups and open three-point groups with i as the vertex and T_{ri} is the number of triangles that represent two of three points being connected.

The clustering coefficient is an important parameter describing small-world networks, which are defined as networks with large clustering coefficients and short average paths. In such networks, most nodes are not adjacent to each other, but the neighbors of any given node are likely to be adjacent to each other, and most nodes can be accessed through other nodes in fewer steps or jumps. In the transport network based on the Space-P method, the clustering coefficient represents the connection relationship between a stop and other stops that can be reached without transfer and the connection relationship of these other stops. The higher the index is, the better the reachability between these stops is. The higher the average clustering coefficient is, the closer the structure of the entire transport network is and the stronger the reachability between the stops is.

4.3. Path Length in Space-P Transport Networks

There are one or more paths between any two nodes in an undirected complex network. The path with the least number of nodes is the shortest path between two nodes, and its length is the number of nodes contained in the shortest path. The maximum length of the shortest path between nodes in a network is called the network diameter and is used to describe the scale of a complex network, as shown in Equation (5):

$$D = \max_{i,j} d_{ij} \tag{5}$$

where d_{ij} is the shortest path length of node i and node j. On this basis, the average shortest path between all connected nodes in a network with N nodes is the average path length of the network, also known as the characteristic path length of the network. The formula is given in Equation (6):

$$L = \frac{2}{N(N+1)} \sum_{i \geq j} d_{ij} \tag{6}$$

In real networks, the scale is usually large and the number of nodes is large, but the average path length is small. This is because real networks tend to have small-world characteristics, where the average degree of the network node and the increase rate of the average path length is proportional to the logarithm of the number of network nodes. In the transport network based on the Space-P method, the path length between two points represents the number of transfers from one stop to another stop, and the path length of 1 indicates that the two stops can reach each other without transfer. The average path length of the entire network represents the average number of transfers connecting two stops in the network.

4.4. Integrated Centrality in Space-P Transport Networks

Centrality analysis is an important part of network characteristics analysis, which is used to measure the importance of nodes in the network. It generally includes degree centrality, closeness centrality, harmonic centrality, eigenvector centrality, betweenness centrality, etc. Degree centrality is the number of other nodes that are directly connected to a node. If a point is directly connected to many points, then the point has a higher degree centrality. Closeness centrality is the reciprocal of the sum of the shortest distance between a node and all other points in the network, and the closer a point is to other points, the less dependent it is on other nodes in transmitting information, the higher the closeness centrality of the point. Harmonic centrality is the reciprocal of the harmonic mean of the shortest distance between a node and other nodes, and the distance of unreachable nodes is 0. Harmonic centrality is a special case of closeness centrality, and the "average shortest distance" proposed by harmonic centrality is the reciprocal sum of these shortest distances. Eigenvector centrality represents the degree of connection between a node and other important nodes. Nodes with higher eigenvector centrality are usually connected to other important nodes and have more resources and information. Betweenness centrality represents the number of times a node appears on all the shortest paths, and nodes with higher betweenness centrality act as bridges in the network, connecting different communities and subnetworks. Each index reflects the importance of nodes in the network from different angles. To improve the comprehensiveness and accuracy of key node identification, the above five types of centrality indicators are calculated by arithmetic average, which is called integrated centrality [39].

In the Space-P transport network, degree centrality reflects the ability of a stop to reach other stops directly. Closeness centrality can reflect the minimum transfer times between a stop and all other stops on the network that can be reached directly or through transfer; it represents how easy it is for the stop to reach other stops on the network. Based on the closeness centrality, the harmonic centrality takes into account the other stops that cannot be reached directly or by transfer, which can more accurately reflect the difficulty of a stop to reach all the stops on the whole network. Eigenvector centrality reflects the degree of connection between a stop and other important transfer points on the transport network. The greater the value, the better the reachability of the stop to other stops. Betweenness centrality indicates whether a stop is located on the shortest path of all two stops. The larger the value, the more critical the stop is to improve the efficiency of the transport network. Integrated centrality indicates the degree of influence of a stop on the network connectivity, stop transfer, and network operation efficiency, and can be used to identify the key stops in the transport network.

5. Empirical Research—Construction of Xi'an's Public Transport Network

5.1. Brief Introduction to Xi'an's Public Transport Network

The data for this study were obtained from the service address provided on open platform website Baidu. As of September 2022, Xi'an has eight metro lines and 163 stops in operation, with a total operating mileage of 242.952 km and an average daily passenger volume of 2.1 million people. Xi'an has 1984 bus lines and 3283 bus stops, carrying 1.55 million passengers per day. In addition to its six closely connected administrative regions, the city of Xi'an has several relatively dispersed areas, such as Yanliang, Gaoling, Huyi, and Changan. These dispersed areas are not conducive to the analysis being conducted on the level of the whole network, so the research scope of this article is focused on the six administrative regions of Yanta, Beilin, Xincheng, Weiyang, Lianhu, and Baqiao, represented as grey areas in Figure 6.

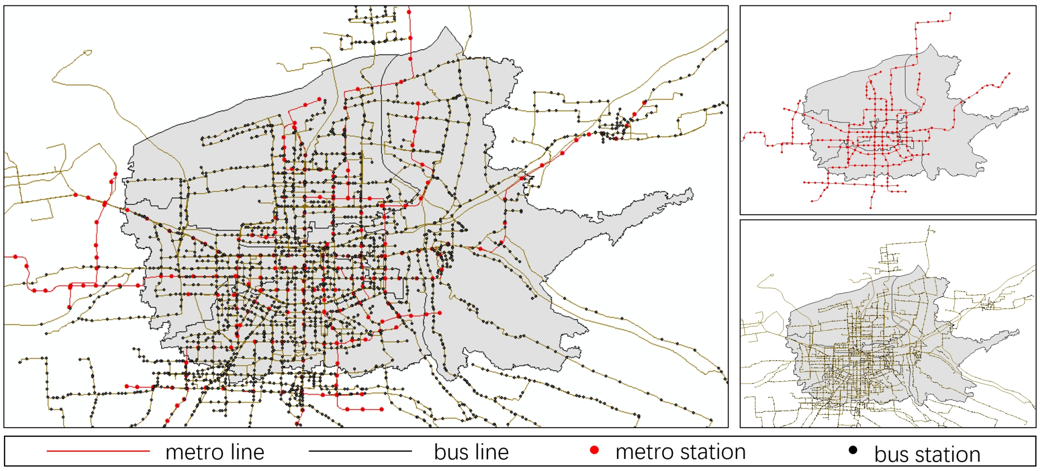


Figure 6. Xi'an composite metro–bus network and its two-layer subnetworks.

Xi'an is located in the center of the China, with coordinates: longitude 108 east, latitude 34 north. By the end of 2023, Xi'an had a population of 13 million, making it the 7th most-populated city in China. Moreover, it has 5.3 million vehicles, ranking 6th among cities in China, 311 km of metro lines, ranking 12th in the country, and 570 million annual passenger trips on bus transportation, ranking 9th in the country.

5.2. Construction of Xi'an Metro–Bus Composite Network Based on Space-P Model

The network construction steps are as follows:

(1) Adjacency matrix construction for the metro subnetwork and bus subnetwork. The adjacency matrix is constructed based on the Space-P method after processing the original data. A total of 90,659 lines are constructed for every two connected stops. Stops on different lines are regarded as different stops, and the number of total stops is 8519. There are 117 stops and 1219 stops connected to each stop on each metro line.

(2) Weight matrix construction: Among the edges delineated above, some have the same start and end points. Our processing method requires that two points have only one edge. If there are n lines connecting the two points, the edge is weighted with weight n, and the weight matrix of each subnetwork is constructed based on this idea. After processing, the total number of stops is reduced from 8519 to 1783, and the number of edges is 74,817. In the metro network, the number of connected edges with the same starting and ending points is at most one, so the weight matrix is the same as the adjacency matrix.

(3) Bus subnetwork transfer edge connections: Based on the method of identifying transfer relationships within transit networks mentioned in this paper, 2909 bus transit relations are identified in Xi'an, and the edges in the network are connected. Considering the factor of the single-mode transfer of bus subnetworks, the bus network in Xi'an has 77,726 connecting edges and 1951 nodes.

(4) Bus–metro transfer side connections: A total of 419 metro and bus transfer relations are identified in Xi'an based on the method of identifying transfer relationships within metro–bus networks mentioned in this paper, and the edges in the network are connected. The composite metro–bus network includes a bus network, a metro network, and a transfer network between the bus and metro, with a total number of 2068 nodes and 79,364 edges. Through the above data processing and combined with Gephi network mapping software, Xi'an's metro–bus composite network and its two-layer Space-P subnetwork are drawn, as shown in Figure 7.

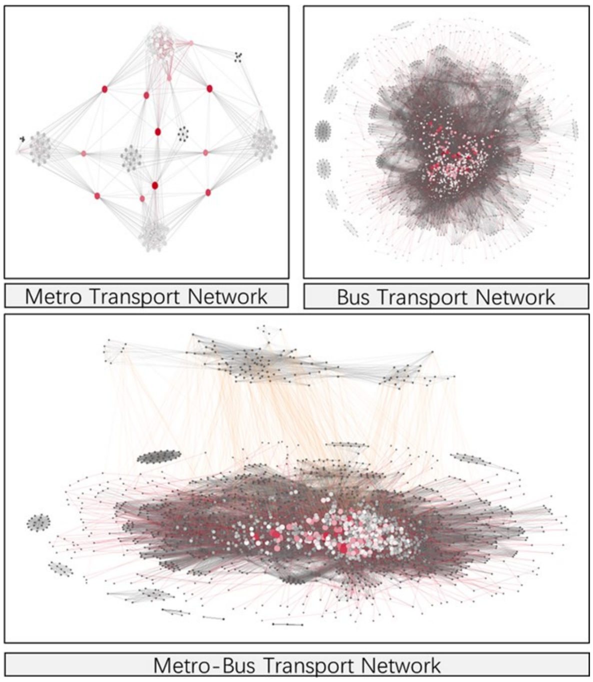


Figure 7. Xi'an composite metro–bus network and its two-layer Space-P network.

6. Results and Discussion

6.1. Scale-Free Characteristic Analysis Based on Degree and Point Intensity Distribution

In a transport network, the distribution of degree values and point intensity reflects the bearing capacity and transport capacity of the nodes in the network and can be used to judge whether the network has scale-free characteristics. Through hierarchical topology analysis, the degree distribution diagrams in Figure 8 and point intensity distribution diagrams in Figure 9 can be obtained for the metro network layer, bus network layer, and two-layer metro–bus network. As can be seen from the figures, Xi'an's metro network, bus network, and metro–bus network obey the power-law distribution on the whole, indicating that these networks all have scale-free characteristics. Only a few stops in each network have strong connectivity; these stops play a key role in the connection of the whole network and are the network's core stops. Most stops are directly connected to only a few other stops.

6.2. Small-World Characteristics Analysis Based on Average Path Length and Clustering Coefficient

If a network has a smaller average path length and a larger clustering coefficient compared to random networks of the same scale, the network has small-world characteristics. Therefore, the average path length and clustering coefficient of random networks which have the same number of nodes and edges as the metro network, bus network, and metro–bus composite network are calculated and compared, as shown in Table 1. In the table, MTN represents the metro network; BTN represents the bus network; MBTN represents the metro–bus network; and RN1, RN2, and RN3 represent the random metro network, bus network, and metro–bus composite network used for comparison.

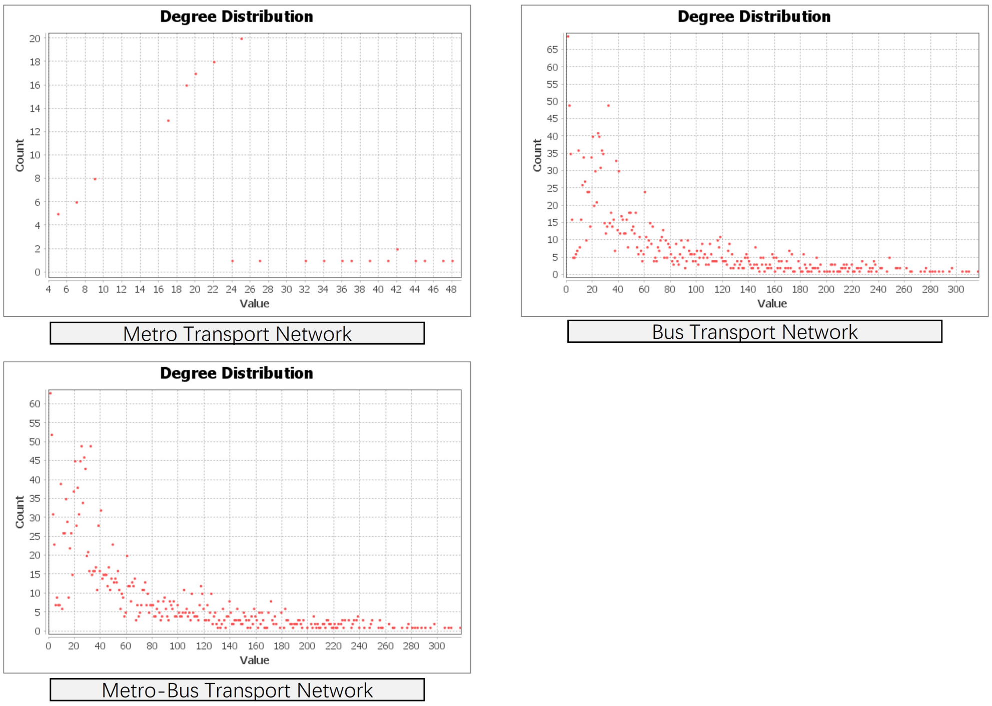


Figure 8. Degree distribution of the metro network, bus network, and two-layer metro–bus network.

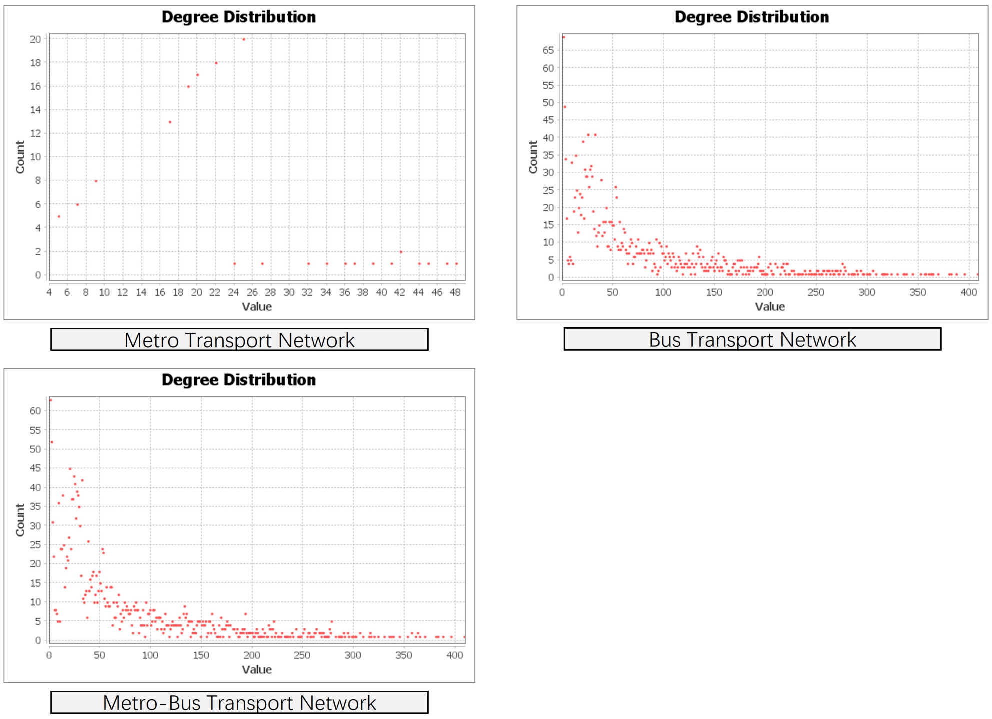


Figure 9. Point intensity distribution of the metro network, bus network, and two-layer metro–bus network.

Table 1. Index comparison between Xi'an's metro–bus composite network and its two subnetworks and random networks of the same scale.

	MTN	RN1	BTN	RN2	MBTN	RN3
Number of nodes	117	117	1951	1951	2068	2068
Number of edges	1219	1219	77,726	77,726	79,364	79,364
Average path length	2.051	3	2.658	3	2.707	3
Agglomeration coefficient	0.944	0.177	0.560	0.180	0.563	0.037

As can be seen from Table 1, compared with random networks of the same scale, the Xi'an metro network, bus network, and metro–bus composite network all have smaller average path lengths and larger clustering coefficients, indicating that they all have small-world network characteristics. The average path length of the metro network is the smallest among the three networks, and the clustering coefficient is the largest, indicating that the metro network layer has high agglomeration and a community structure. However, the average path length and clustering coefficient of the composite metro–bus network are almost the same as that of the bus network. It can be seen that the addition of the metro network has a limited influence on the connectivity of the entire public transport network, which is mainly due to the large scale of the bus network and the small scale of the metro network.

6.3. Network Node Importance Ranking and Key Node Identification Based on Integrated Centrality

The degree centrality, closeness centrality, harmonic centrality, eigenvector centrality, and betweenness centrality of the bus network, metro network, and metro–bus composite network were calculated. The five indexes of centrality are added together on average as an integrated centrality after standardization, and sorted in order from largest to smallest. The top 20 stops are classified, to carry out classification management of these stops. The top 20 nodes with the largest integrated centrality and the stop classification in each network are shown in Table 2. The ranking reflects the differences in the impact of these stops on the overall network connectivity, accessibility, network operation efficiency, etc.

It can be seen from the data in Table 2 that the integrated centrality of the first eight stops in the metro network layer is higher than that of the bus network layer and the first level of the metro–bus composite network, indicating that the overall performance of several stops in the metro network that play a major role in the network is better than that of the bus network or the metro–bus composite network. From the results of classification, in the metro network, the first 20 stops are divided into 12 levels, and the bus network and the metro–bus composite network are divided into 7 levels. The top 10 stops are divided into nine, five, and four classes, respectively, in the metro network, bus network, and the metro–bus composite network. It can be seen that the difference between the main stops in the metro network is greater than that between the bus network and the metro–bus composite network. The stop of each layer of the network is classified and can be used for stop differentiation management. By comparing the important nodes of the metro–bus composite network and the single-layer network of metro and bus, the integrated centrality value of the metro–bus composite network is almost the same as that of bus network, but the ranking differs to some extent. For example, the rankings of the integrated centrality values of bus stops such as Dayan Pagoda North Square, Banpo Bus dispatching stop, administrative center, Nanmen Gate, Chanhe River, and South entrance of Labor South Road are higher than the rest of the network, indicating that the metro–bus transfer relationship of these stops is more important. To improve the connectivity of the whole bus network, more attention should be paid to the optimization of the transfer links between bus stops and metro stops.

Table 2. Ranking of the top 20 nodes with the largest integrated centrality index values in the three types of networks.

Rank	BTN			MTN			MBTN		
	Level	Integrated Centrality Value	Node	Level	Integrated Centrality Value	Node	Level	Integrated Centrality Value	Node
1	1	3.6944	Youjiazhuang	1	4.7561	Tonghuamen	1	3.5076	Youjiazhuang(B)
2	2	3.5107	Dachaishi	2	4.5695	Dayanta	2	3.4486	Dayantabei -guangchang(B)
3	3	3.4611	Wulukou	3	4.4843	Qinglongsi	2	3.4304	Banpo -gongjiao -diaoduzhan(B)
4	3	3.4327	Beidajie	4	4.3895	Xi'anbeizhan	2	3.4292	Dachaishi(B)
5	3	3.4110	Banpo -gongjiao -diaoduzhan	5	4.2181	Jianzhukejidaxue -Lijiacun	3	3.3895	Xingzheng -zhongxin(B)
6	4	3.3973	Xingzheng zhongxin	6	4.1800	Wulukou	3	3.3851	Beidajie(B)
7	4	3.3588	Yuxiangmen	7	4.0902	Xiaozhai	3	3.3783	Wulukou(B)
8	4	3.3088	Minleyuan	8	3.7628	Nanshaomen	4	3.2839	Nanmenwai(B)
9	4	3.3022	Tumenxi	8	3.7195	Beidajie	4	3.2754	Shitushuguan(B)
10	5	3.2953	Shitushuguan	9	3.6588	Kejilu	4	3.2726	Yuxiangmen(B)
11	5	3.2837	Dayanta beiguangchang	9	3.6391	Shuangzhai	4	3.2133	Minleyuan(B)
12	5	3.2827	Nanmenwai	10	3.4515	Xingzheng -zhongxin	5	3.1688	Tumenxi(B)
13	6	3.1646	Gaoxinluke -jilukou	11	2.9790	Fangzhicheng	5	3.1229	Chanhe(B)
14	6	3.1450	Taihualuzi -qianglukou	12	2.8932	Baoshuiqu	6	3.0718	Gaoxinluke -jilukou(B)
15	6	3.1116	Beiguan	12	2.8932	Xinzhu	6	3.0718	Taihualuzi -qianglukou(B)
16	7	3.0899	Tumen	12	2.8932	Guojigangwuqu	6	3.0427	Tumen(B)
17	7	3.0739	Nanshaomen	12	2.8932	Wuzhuang	6	3.0326	Nanshaomen(B)
18	7	3.0612	Chanhe	12	2.8932	Xianghuwan	6	3.0280	Beiguan(B)
19	7	3.0369	Zhuquemen	12	2.8932	Chanbazhongxin	7	2.9647	Weiyanglufeng -chengwulukou(B)
20	7	3.0286	Weiyanglufeng -chengwulukou	12	2.8932	Taohuatan	7	2.9529	Laodongnan -lunankou(B)

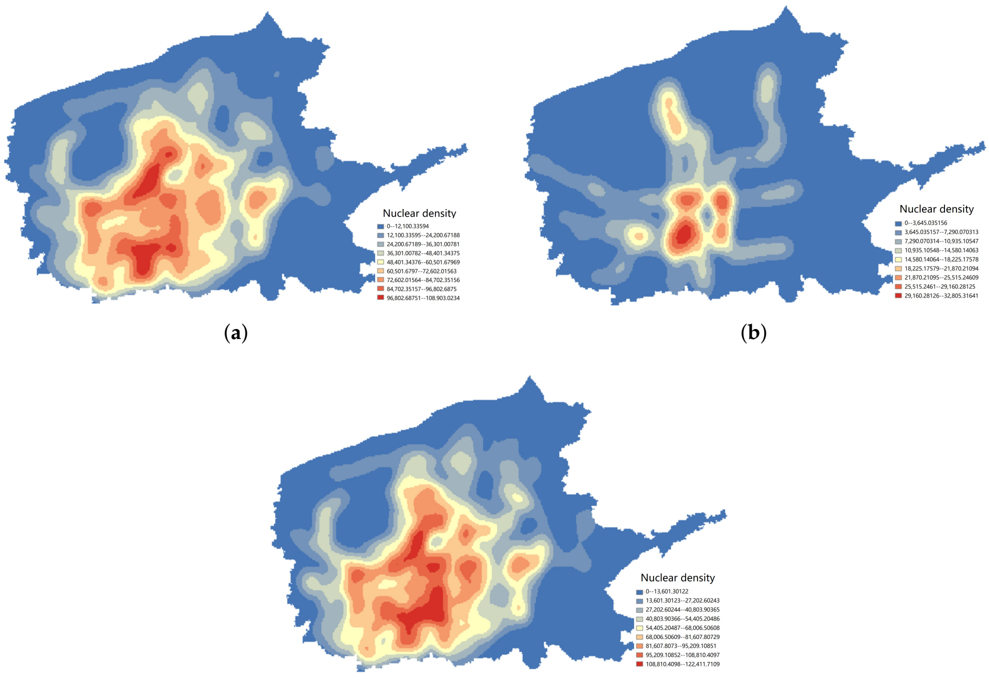
The distributions of integrated centrality in the BTN, MTN, and MBTN are shown in Figure 10. As can be seen from the figure, Xi'an's BTN has a large coverage area, showing a dual-core "central+southern" network. There is a small range of core areas in the economic development zone and near the high-speed rail stop in the north of the city. Moreover, the bus stops in the west of the city have a weak influence, and the bus stops in the east of the city have the least influence on the whole network's connectivity. Due to the small number of metro lines in Xi'an, the core area of the metro network is mainly distributed in the central and southern parts of the city, which is relatively concentrated. Unlike the central and southern parts, the northern part of the city shows a weak core area feature and the influence of the network connectivity in other areas is generally weaker than that in the core area. The MBTN superimposes the bus transport network on the metro transport network. Due to the large volume of bus stops, the stop centrality of the MBTN is similar to that of BTN. However, after superimposing the MTN, the number of stops affecting the connectivity of the entire network increases, and the network shows closer connections between stops and a more balanced network.

6.4. Analysis of Direct and Transfer Characteristics of the Network Based on Degree and Weight Degree

The stops in Xi'an's metro network, bus network, and metro–bus composite network are ranked based on degree and weight degree in Table 3.

In the metro network, the ranking of degree and weighting degree is consistent, and the top ten stops with degree value are all metro transfer stops, among which the Xi'anbeizhan stop is the transfer stop of Line 2 and Line 4, Dayanta is the transfer stop of Line 3 and Line 4, Qinglongsi is the transfer stop of Line 3 and Line 5, Tonghuamen is the transfer stop of Line 1 and Line 3, and Xiaozhai is the transfer stop of Line 2 and Line 3. Moreover, Jianzhukejidaxue·Lijiacun is a transfer stop of Line 4 and Line 5, Wulukou is a transfer stop of Line 1 and Line 4, Xingzhengzhongxin is a transfer stop of Line 2 and Line 4, Nanshaomen is a transfer stop of Line 2 and Line 5, and Beidajie is a transfer stop of Line 1 and Line 2.

In the bus network, the ranking of degree and weight degree are not completely consistent. Dachashi stop has the highest degree and weight degree value, and the subsequent ranking is slightly different. Combined with the geographical location of each stop, it can be found that among the bus stops of Xi'an, the areas with high degree and weight degree are mainly concentrated in the first ring road and the inner ring road, including Dachashi, Yuxiangmen, Wulu kou, Beidajie, Minleyuan, and other areas within the first ring road. Dayantabeiguangchang is a famous tourist attraction, Nanmenwai and Nanshaomen are the core areas of the south of Xi'an, and Tumen is the core area of the west Ring Road. It can be seen that the first ring road of Xi 'an's public transport network has the highest degree of direct transport to stops. In recent years, with the expansion of Xi'an and the transfer of the core business circle, the core area of Xi'an has gradually spread from the Wulukou business circle and Beidajie business circle to the south and north of the city. However, through the analysis of the structure of the bus network, it can be seen that the bus lines still have a large capacity to the old city, which may be caused by the line planning lagging behind the urban development.



(**a**) (**b**)

(**c**)

Figure 10. The nuclear density of BTN, MTN, and MBTN based on integrated centrality. (**a**) The nuclear density of BTN based on comprehensive centrality. (**b**) The nuclear density of MTN based on comprehensive centrality. (**c**) The nuclear density of MBTN based on integrated centrality.

Table 3. Ranking of the top 10 nodes with the highest degree and weight degree in the three types of networks.

Rank	BTN		MTN		MBTN	
	Degree	**Weight Degree**	**Degree**	**Weight Degree**	**Degree**	**Weight Degree**
1	Dachaishi	Dachaishi	Xianbeizhan	Xianbeizhan	Dachashi(B)	Dachashi(B)
2	Yuxiangmen	Wulukou	Dayanta	Dayanta	Nanmenwai(B)	Yuxiangmen(B)
3	Nanmenwai	Yuxiangmen	Qinglongsi	Qinglongsi	Yuxiangmen(B)	Wulukou(B)
4	Wulukou	Nanmenwai	Tonghuamen	Tonghuamen	Wulukou(B)	Nanmenwai(B)
5	Youjiazhuang	DayantaBei guangchang	Xiaozhai	Xiaozhai	Beidajie(B)	DayantaBei guangchang(B)
6	Tumenxi	Beidajie	Jianzhukejidaxue -lijiacun	Jianzhukejidaxue -lijiacun	Youjiazhuang(B)	Beidajie(B)
7	Beidajie	Xingzhengzhongxin	Wulukou	Wulukou	Tumenxi(B)	Tumen(B)
8	Minleyuan	Tumenxi	Xingzheng zhognxin	Xingzheng zhognxin	DayantaBei guangchang(B)	Tumenxi(B)
9	Nanshaomen	Minleyuan	Nanshaomen	Nanshaomen	Minleyuan(B)	Minleyuan(B)
10	DayantaBei guangchang	Tumen	Beidajie	Beidajie	Nanshaomen(B)	Xingzheng zhognxin(B)

In the bus–metro composite network, the ranking of degree and weighting degree is basically the same as that of the bus network, which is less influenced by the metro network. It can be seen that for the public transport system of Xi'an, the number of stops and lines in the metro network accounts for a relatively low proportion compared with the number of conventional buses, which cannot have an important impact on the site connectivity of the whole public transport network.

Based on the degree values in the complex network model, this paper determines the degree distribution of each stop in Xi'an's MTN and BTN, the distribution of direct lines at each stop, and the linear density based on direct lines, as shown in Figure 11. As can be seen from Figure 11a,c,e, the central and southern regions of Xi'an's metro transport network are the regions with the highest network accessibility, and the number of stops that can be reached by a single ride in these regions is the largest. The range of accessibility outside the core area shows a declining circle, which is consistent with the state of the metro network and the urban development of Xi'an. As can be seen from Figure 11b,d,f, consistent with the metro network, the stops with the highest direct access in Xi'an's bus transport network are also concentrated in the central and southern areas of the city. Due to the large volume of lines and stops, direct access to stops in this network is better than in the metro transport network, and the direct access trend is characterized as "the single core is dominant, and the circle diffusion weakens step by step".

At present, the city of Xi'an shows characteristics of multi-center urban development. Attention should be paid to the development of public transport at all central points, so as to improve the direct access of public transport stops in the multi-center area, optimize the public transport network, and promote the realization of green and efficient urban patterns.

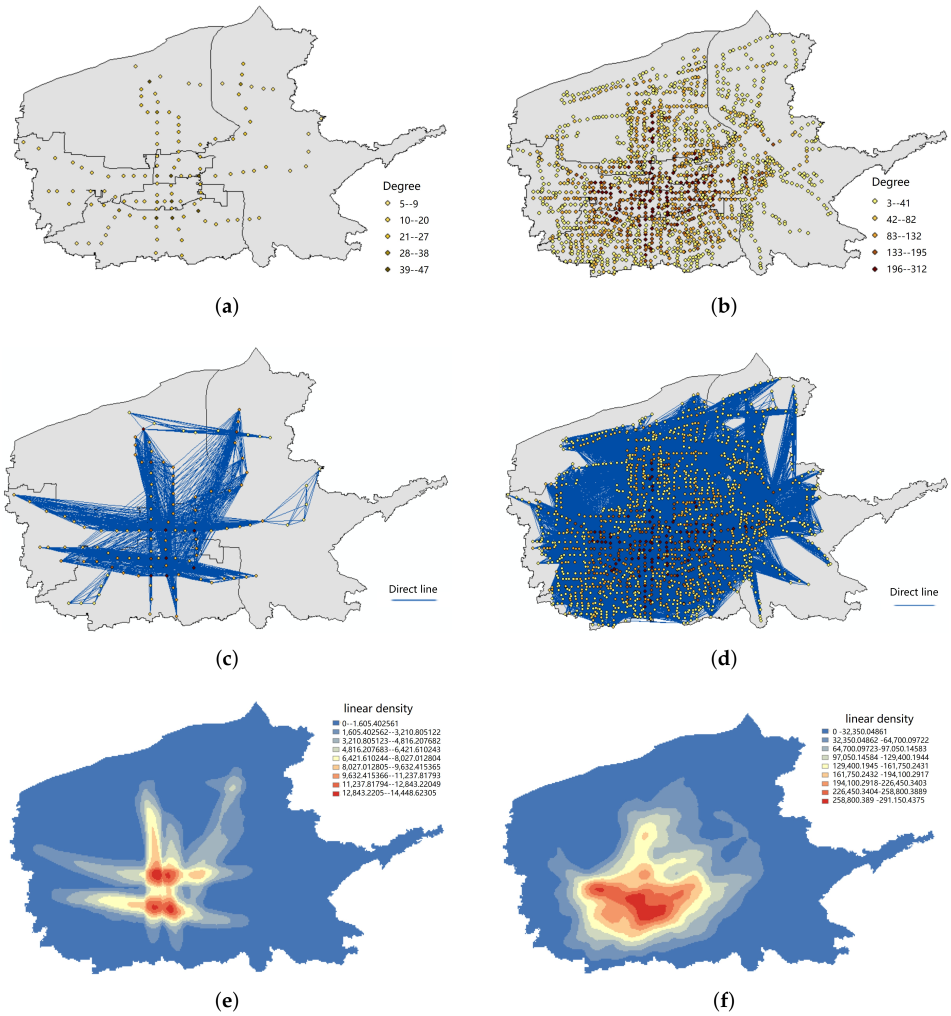


Figure 11. Direct analysis of the MTN and BTN. (**a**) Stop degree of MTN based on Space-P. (**b**) Stop degree of BTN based on Space-P. (**c**) Stop direct line of MTN based on Space-P. (**d**) Stop direct line of BTN based on Space-P. (**e**) Linear density of direct line of MTN based on Space-P. (**f**) Linear density of direct line of BTN based on Space-P.

7. Conclusions

This paper builds a transport network based on the Space-P method, aiming to highlight the transfer characteristics of transport stops. In the identification of stop transfer relationship, the transfer relationship between bus and bus is identified based on the hypernode diagram representation, and the transfer relationship between bus and metro is identified based on the reasonable time of walking transfer. The scale-free and small-world characteristics of the network are identified by the degree and degree distribution, clustering coefficient, and average path length at the macro level. Furthermore, the paper introduces the concepts of centrality in complex networks, such as degree centrality, closeness centrality, harmonic centrality, eigenvector centrality, and betweenness centrality, into multi-layer Space-P transport transfer network, giving each index practical significance in transport transfer network. Based on the comprehensive consideration of network connectivity, direct access, stop transfer relationship, and network efficiency, the key nodes that restrict the development of network optimization are identified. Finally, combined with the geographical coordinates of public transport stops, this paper summarizes the geographical structure characteristics of Xi'an public transport network in terms of stop influence, stop direct access, stop transfer, line density, and other aspects based on ArcGIS software. The above research can provide a scientific basis for the formulation of regional and hierarchical transfer relationship optimization, line density optimization, and efficiency improvement strategies for public transport networks. The main conclusions are as follows:

(1) Xi'an's metro–bus composite network and its subnetwork layer both have scale-free characteristics. Both the metro layer and the bus layer have a few nodes with a large number of connections, and the scale-free characteristic of the bus network layer is noticeably greater than that of the metro network layer.

(2) Compared with random networks of the same scale, Xi'an's metro network, bus network, and metro–bus composite network all have a small-world characteristic, and the average transfer times of the three types of networks are 2, 2.6, and 2.7, respectively, indicating that the direct transport between any two points in the metro network is better than that of the bus network. However, the scale of the metro network is small, so it does not improve the directness of the whole public transport network.

(3) The influence of the key stops of the metro network is higher than that of the bus network, and it is mainly concentrated in a few stops, and the normal operation and optimization of these stops are crucial to the development of the network. The key stops of the bus network are relatively dispersed and the differences are small. The influence of the key stops of the metro–bus composite network is basically the same as that of the bus network, which may be related to the large volume of the bus network.

(4) Xi'an's bus transport network covers a large area, showing the characteristics of a dual-core "central + southern" network. The core area of the Xi'an metro transport network is mainly distributed in the central and southern parts of the city. The composite metro–bus network has fewer connections between stops and a more balanced network.

(5) From the degree and weight degree ranking, it can be seen that the directness of Xi'an's public transport network on 1st Ring Road is the highest. The core areas in the south, west, and north of the city also have high degrees of directness, while the directness in the east of the city is slightly lower. At present, route planning is lagging behind the multi-center development of Xi'an.

(6) From the degree distribution and linear density map of BTN and MTN, it can be seen that the central area and the southern area of Xi'an have strong direct access, and the number of stops that can be reached by a single ride is the largest in these networks. The direct access of stops shows the characteristic of "the single core is dominant, and the circle diffusion weakens step by step".

To sum up, the overall development of the public transport network in Xi'an conforms to the basic structural characteristics of complex networks. There exist some key stops that play a vital role in the connectivity of the networks. Therefore, it is necessary to strengthen the maintenance of such metro stops and alleviate transport around bus stops to ensure the normal operation of the whole public transport network. In the metro–bus composite network, it takes an average of 2.7 transfers to connect two stops, which requires further optimization to improve the convenience of the whole public transport network.

This paper empirically analyzes the basic structural characteristics of Xi'an's public transport network, taking the heterogeneous nodes and edges of the urban public transport system as the research topic. However, the characteristics of Xi'an's public transport network were only analyzed from a static perspective, without considering the technical and economic characteristics of metro and bus networks, such as speed punctuality, passenger flow volume, and so on. In the follow-up study, a dynamic model of the transport network will be constructed to analyze the structural characteristics of the urban public transport network in more depth.

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