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Exploring the Multi-Layer Structural Properties of the Bus-Subway Transportation Network of Shanghai

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Abstract

Buses and subways are essential to urban public transportation systems and an important engine for activating high-quality urban development. Traditional multi-modal transportation networks focus on the structural feature mining of single-layer networks or each layer, ignoring the structural association of multi-layer networks. In this paper, we examined the multi-layer structural property of the bus-subway network of Shanghai at both global and nodal scales. A dual-layer model of the city's bus and subway system was built. Single-layer complex network indicators were also extended. The paper also explored the spatial coupling properties of the city's bus and subway system and identified its primary traffic nodes. It was found that 1) the dual-layer network increased the network's connectivity to a certain extent and broke through the spatial limitation in terms of physical structure, making the connection between any two locations more direct. 2) The dual-layer network changed the topological characteristics of the transit network, increasing the centrality value and bit order in degree centrality, betweenness centrality, and closeness centrality to different degrees, and making each centrality tend to converge to the city center in spatial distribution. Enhancing the management of critical network nodes would help the integrated public transportation system operate more effectively and provide higher-quality services.

Keywords

Urban Transportation, Structural Characteristics, Dual-Layer Network, Centrality

1. Introduction

China has gradually increased the importance of building a solid transportation nation since the 19th National Congress and has released several guidelines and policies, including *Outline of the Construction of a Strong Transportation Country*, *Outline of the National Comprehensive Three-Dimensional Transportation Network Planning*, *Outline of the 14th Five-Year Plan of the National Economic and Social Development of the People's Republic of China*, and *Outline of the National Comprehensive Three-Dimensional Transportation Network Planning*. The introduction of the guidelines has clarified the vision of the country's future development and highlighted the importance of transportation construction, especially the strengthening of the construction of integrated three-dimensional transportation networks. Studies have been focused on transportation network characteristics [1], network structure evolution [2], and cross-regional transportation synergy [3]. Traditional transportation network analysis is typically restricted to single-layer networks, like bus networks [4] and subway networks [5] [6]. These networks have been found to have properties like small-world or scale-free [7] [8], hierarchical [9] [10], robustness or resistance to destruction [5] [6], which help to optimize traffic flow.

With the continuous promotion of urban integrated three-dimensional transportation network construction, multi-modal transportation networks have received increasing attention. The research has experienced the development from a single-layer network formed by the aggregation of multiple traffic modes [11] [12] to a bipartite network [13] and then to a hierarchical network [14]. These approaches either consider site coupling or focus on the spatial dependence between different types of nodes, each with advantages and shortcomings. For example, when various transportation networks are combined, cross-layer information is practically mixed unpredictably, and examining the combined network rather than the overall multi-layer system may produce inaccurate and misleading conclusions [15]. The bipartite network can portray the connected edge relationship between different nodes [13] but ignores the association between similar nodes. The hierarchical network treats each layer as an independent network without considering the inter-layer connection, which cannot reflect the situation of a virtual traffic network [16].

Multi-layer network analysis methods can effectively overcome the shortcomings of complex network analysis and provide an effective tool for multi-modal traffic network structure mining. There are two standard methods for constructing multi-layer networks, namely, tensor-based methods and super-adjacency matrix-based methods [17], based on which scholars have developed centrality metrics [18] [19], association structure detection algorithms [20] [21], and growth and evolution of multi-layer networks [22]. Multi-layer networks were found to be more effective in identifying the nodes with the highest cohesiveness compared to single-layer and hierarchical networks [15] [23]. Compared to fruitful theoretical studies, there are fewer empirical studies on multi-layer networks. It mainly deals with the relationship between streets and sidewalks [24], different growth strategies of bike lanes and non-bike lanes [25], and changes in the structure of street and subway multi-layer networks [26]. Currently, multi-layer network studies are mostly limited to theoretical discussions, and there is a lack of empirical studies on multi-layer networks of different traffic patterns.

Bus and subway networks are important media and channels for human movement and logistics. In this research, we present a multi-layer network analysis model, combine the multi-layer network framework with quantified coupling station rules, and design a bus-subway double-layer network using Shanghai as an example, which has the most extended subway travel in the world. The spatial coupling properties of the urban bus-subway network are investigated, and its central traffic nodes are found by comparing the structural characteristics of the bus network, subway network, and bus-subway dual-layer network. The outcomes are anticipated to improve the empirical research of multi-layer networks and offer theoretical guidelines for Shanghai's transportation network's spatial optimization.

2. Materials and Methods

2.1. Definition of Multi-Layer Network

A multi-layer network consists of two or more single-layer networks and considers intra-layer and inter-layer connections. Its mathematical definition is $M=\left(L,\boldsymbol{G},\mathrm{g}\right)$, where L is the set of layers, denoted as $L=\left\{\alpha \mid \alpha\in\left\{1,2,\cdots,M\right\}\right\}$. $\boldsymbol{G}$ is a vector that represents the layers, *i.e.*, $\boldsymbol{G}=\left(G_1,G_2,\cdots,G_\alpha,\cdots,G_M\right)$. Where $G_\alpha=\left(V_\alpha,E_\alpha\right)$ represents the network at layer *α*, containing nodes V_α and intra-layer edges E_α, respectively. $\mathrm{g}=\left(V_\alpha,V_\beta,E_{\alpha,\beta}\right)$ characterizes the inter-layer bipartite network composed of a node-set *α* and node-set *β*. *α* and *β* originate from different layers, and $E_{\alpha,\beta}$ is the inter-layer connection, which portrays the interactions between different layer pairs [17].

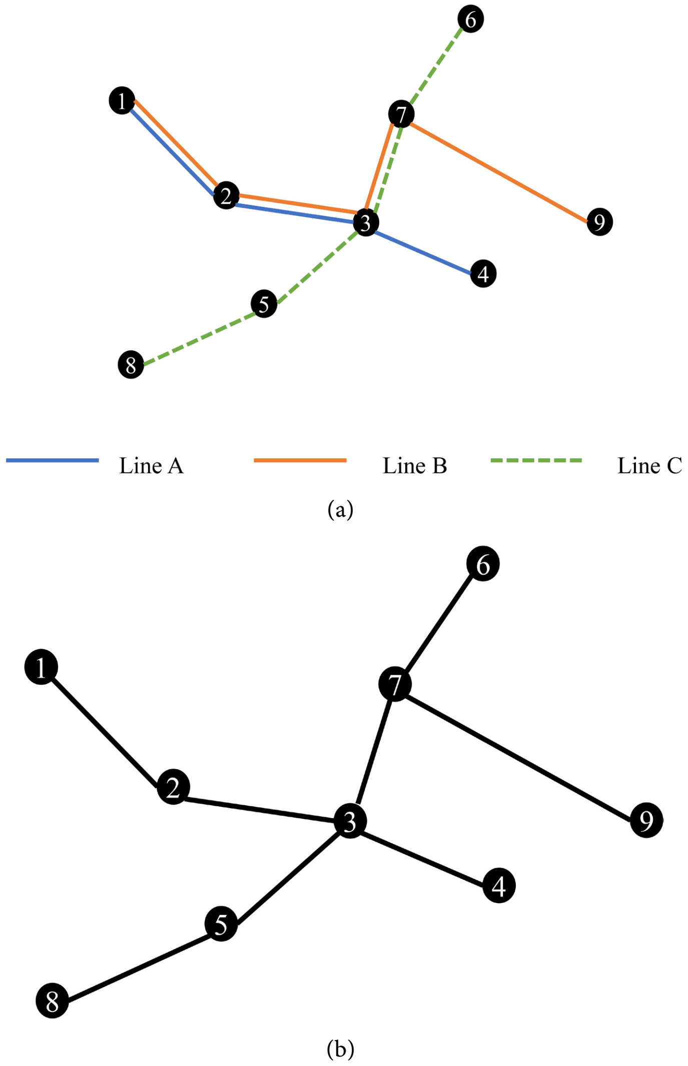
Multi-layer networks are usually represented in two ways, *i.e.*, the tensor-based form and the super-adjacent matrix-based form [27]. The tensor originates from mechanics as a generalization of the vector concept, where the tensor of order 0 is a scalar, the tensor of order 1 is a vector, and the tensor of order 2 is a matrix [13]. For a multi-layer network *M*, its tensor form is expressed as $\left\{x_i\otimes l_\alpha;1\le i\le N,1\le\alpha\le M\right\}$, where *M* denotes having *M* layers and *N* denotes having *N* nodes per layer. This approach is more suitable for multiplex networks, *i.e.*, the nodes in each network layer correspond. The second approach is based on the form of a super-adjacency matrix, which can be expressed as $\tilde{A}=\begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & A_{22} & \cdots & A_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ A_{M1} & A_{M2} & \cdots & A_{MM} \end{pmatrix}\in\mathbb{R}^{NM\times MN}$, where the superadjacency matrix is the adjacency matrix within each layer of the network on the main diagonal, and the non-main diagonal matrix is the adjacency matrix of the interlayer network. The latter is more suitable for use in public transportation network modeling than the former method.

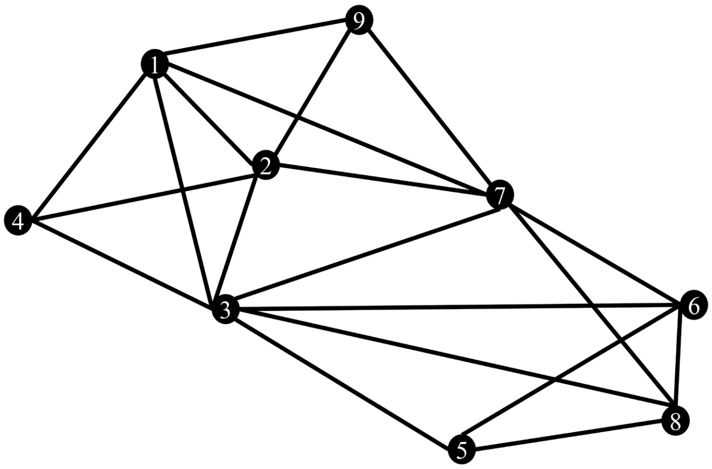
2.2. Representation of the Multi-Layered Bus-Subway Transportation Network

1) Construction of bus and subway sub-networks

In this paper, a dual-layer network is constructed for Shanghai buses and subways, and the process includes bus and subway sub-networks and inter-layer network construction. For the bus and subway sub-networks, the traditional complex network abstraction methods mainly include the L-space-based and P-space-based methods [28]. **Figure 1** shows the form of modeling based on the two spatial approaches.

The L-space-based method treats stations as nodes; each station is only connected to its immediate predecessor and successor stations. This method can effectively reflect the actual topology of the network, mainly focusing on the study





(c)

Figure 1. Network construction of L-space and P-space. (a) Original Line Network; (b) Topology Network of L-space; (c) Topology Network of P-space.

of inter-site connectivity. On the other hand, the P-space-based method abstracts sites as nodes, and when at least one bus or a subway line passes through two sites, there are links between the corresponding nodes of the two sites. This method is often used in the study of interchange and accessibility.

This paper aims to mine the spatial coupling characteristics of the bus-subway dual-layer network and identify the critical traffic nodes in the network by the dual-layer network analysis method. Considering that P-space ignores the spatial proximity characteristics of nodes, this paper selects the L-space method for sub-network modeling.

2) Construction of the interlayer network

The first step of constructing an interlayer network is to find the interchange sites (coupling sites) between the subway and bus. Currently, the commonly used coupling site determination rules are mostly fuzzy class definitions, which do not apply to large-scale networks, so this paper defines the coupling site identification rules quantitatively based on ArcGIS. First, the bus and subway stations are imported into ArcGIS to form two independent layers. We carry out the buffer analysis of any subway station with a distance of 300m. The coupled sites are considered to have lines passing between them, and the related sites are connected to form interlayer edges. The network composed of coupled sites and interlayer edges is the interlayer network.

2.3. Indicators of the Multi-Layer Network

2.3.1. Network Property

1) Feature path length and diameter

A multi-layer network has two or more layers, and the shortest path length is divided into two cases when inter-layer connectivity is considered. When node i and node j are located in the same layer l_m, the shortest path length is the same as the shortest path length of a single network, denoted as $d_{ij}^{l_m}$. When node i

and node *j* are located in different layers l_m and l_n, the shortest path length is the minimum number of edges connecting nodes *i* and *j* across both layers l_m and l_n, denoted as $d_{ij}^{l_m l_n}$. The characteristic path length of a multi-layer network is the average of the shortest paths between any two nodes, and its mathematical expression is $D=\frac{1}{N(N-1)}\sum_{i\neq j}\left(d_{ij}^{l_m}+d_{ij}^{l_m l_n}\right)$. Higher values of characteristic path length indicate more limited subway-bus interchanges (*i.e.*, less developed transportation network) or more loose subway network structure (e.g., urban sprawl), and more long-distance bus routes.

2) Clustering coefficient

The node clustering coefficient in a multi-layer network can be extended from a single-layer network by defining the ratio of the number of edges between all nodes adjacent to a node to the maximum number of possible edges between these adjacent nodes. The number of edges between node *i* in the layer l_m And nodes in the same layer are denoted as $E_i^{l_m}$, and the number of edges between nodes in different layers is denoted as $\sum_{n=1}^{N}E_i^{l_m l_n}$. The clustering coefficient of node *i* can be expressed as $C_i=\frac{2\left(E_i^{l_m}+\sum_{n=1}^{N}E_i^{l_m l_n}\right)}{k_i(k_i-1)}$. The average clustering coefficient of the multi-layer network is the average of the clustering coefficients of all nodes, *i.e.*, $C=\frac{1}{N}\sum_{i=1}^{N}C_i$. The larger the clustering coefficient, the more connected the network is. For bus networks, the higher the clustering coefficient, the more looped routes.

2.3.2. Nodal Centrality

1) Centrality indicators

The different patterns of bus organization networks and subway networks reflect the connectivity of the networks, as well as the scheduling of routes and stations and the setting of service frequencies. The portrayal of the node characteristics of both helps to evaluate the rationality of the facility layout. In this paper, the direct accessibility, relative accessibility, and transit function of bus and subway networks are evaluated in terms of degree centrality, betweenness centrality, and closeness centrality, respectively. The measures of each index are as follows.

Degree centrality is the number of other nodes directly connected to a node. It intuitively reflects the likelihood that a node will be directly connected to other nodes in the network. In general, the higher the degree centrality value of a station, the more bus lines or subway lines pass through the station, and the more convenient the station is for interchange, which is essential for the regular operation of the network. When congestion occurs at a station with a high degree of centrality value, it can bring about traffic paralysis in a large area.

Betweenness centrality describes the degree of distribution of a node on the paths between other nodes, and in transportation networks, reflects the connecting role of the site in the network, which is the "bridge" node in the network.

If a node is on multiple shortest paths of other nodes, then the node is a core node, which is mathematically defined as:

$$C_B(v) = \sum_{s \neq t \neq v \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{1}$$

$\sigma_{st}(v)$ denotes the number of shortest path entries of $s \to t$ through node *v*, and σ_{st} denotes the number of shortest path entries of $s \to t$. The higher the value of betweenness centrality, the more vital the bridging role of the node in the network is. For bus networks, when congestion occurs at a node with high intermediary centrality, it brings about traffic paralysis from that station to the interchange station and the remaining stations. The higher the betweenness centrality, the more significant the impact on the regular operation of the bus network. The same is true for subway lines.

Closeness centrality is used to measure the average distance from a node to other nodes, which reflects the accessibility of a station in a transportation network and is an important indicator to evaluate whether a station is in the center of the network and is mathematically defined as:

$$C_v = \frac{|V-1|}{\sum_{i \neq v} d_{vi}} \tag{2}$$

where $\sum_{i \neq v} d_{vi}$ is the sum of the shortest distances from node *i* to other nodes, and V is the total number of nodes. Closeness centrality reflects the relative accessibility or compactness of the transportation network. Usually, the more compact the urban form and the denser the bus network, the higher the value of neighborhood centrality of bus stops.

The above centrality characteristic values are also calculated and analyzed for subway networks.

2) Intra-layer degree, inter-layer degree, and degree distribution

The above centrality indicators can be naturally extended from a single to a multi-layer network [18]. The node degree of a multi-layer network contains two components: intra-layer degree and inter-layer degree. The intra-layer degree is calculated in the same way as for a single-layer network, *i.e.*, the number of connected edges between node *i* located in layer l_m and other nodes in the same layer network, denoted as $k_i^{l_m}$. The inter-layer degree $k_i^{l_m l_n}$ is the number of connected edges of node *i* located in layer l_m with the corresponding coupling points of the network in other layers. Thus, the degree k_i of node *i* is $k_i = k_i^{l_m} + \sum_{n=1}^{N} k_i^{l_m l_n}$. This indicator expresses the importance of the node in the network.

The degree distribution $P(k)$ is used to describe the distribution of node degrees in the network and is mathematically defined as $P(k) = \frac{n_k}{N}$, which represents the probability that the nodes with a degree equal to *k* account for the total number of nodes. Additionally, to improve the fitting accuracy of the degree distribution, the cumulative degree distribution can also be used to characterize the distribution of node degrees. It is defined as the probability of degree values greater than or equal to *k*, *i.e.*, $P(K \ge k) = \sum_{K=k}^{\infty} p(k)$. The degree distribution of nodes can be used to measure the degree of statistical disequilibrium of node reachability.

2.4. Data Source and Processing

The study area is 16 districts in Shanghai, including Huangpu, Xuhui, Changning, Jing'an, Putuo, Hongkou, Yangpu, Pudong, Minhang, Baoshan, Jiading, Jinshan, Songjiang, Qingpu, Fengxian, and Chongming districts. The data used in this paper include bus and subway data (station name, latitude, longitude, sequence, and line name) and population km grid distribution data. As of September 2021, the bus and subway data are obtained through the API provided by Gaode Map (https://www.amap.com/), where the bus data contain several stations with the same name and different stations, which should be distinguished one by one before modeling according to the multi-layer network definition. Some bus lines extend outside the Shanghai administrative district, and these stations are retained to ensure the integrity of the bus lines. After completing the initial cleaning of the data, the subway stations are 378, and the lines are 18, as shown in **Figure 2**. The number of bus stops is 13,408, and 1391 lines (including only upstream lines).

As mentioned before, the bus stops (by name) are represented as node *b*, then the set of bus network nodes is $B(b_1, b_2, b_3, \cdots, b_i, \cdots, b_{13408})$, and the subway stops (by name) are represented as node *s*, then the set of subway network nodes is $S(s_1, s_2, s_3, \cdots, s_i, \cdots, s_{378})$. The adjacency matrix of the subnetwork is constructed based on the sequence of bus and subway lines and stations, *i.e.*, when

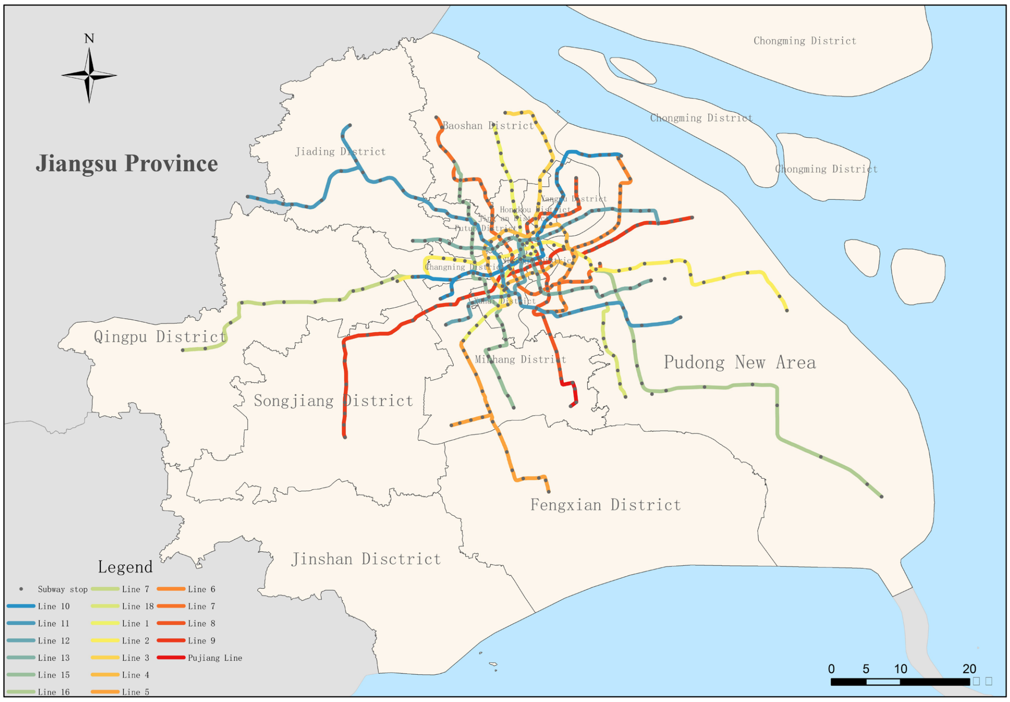


Figure 2. The subway map of Shanghai.

there is a line connection between two nodes, the attribute value one is assigned in the matrix; otherwise, it is 0. This results in 21,491 edges for the bus subnetwork and 438 for the subway subnetwork. As mentioned before, the interlayer edges of the bus-subway network are 923 obtained by the inter-layer network construction method. To better show the intra-layer and inter-layer connections, Figure 3 shows the local area of the Century Avenue subway station in the bus-subway dual-layer network, and some bus lines and stations are not ultimately shown.

The population km grid data is derived from the WorldPop dataset (https://www.worldpop.org/), representing the estimated total number of people per grid cell. It is in the Geotiff format with a resolution of 3 radians (approximately 100 m at the equator), projected in the geographic coordinate system WGS84 in units of people per pixel. Figure 4 shows the distribution of the population km grid in Shanghai.

3. Research Results

3.1. The Hierarchical Structure of the Multi-Layer Network

As mentioned earlier, the indicators that can characterize the multi-layer network structure were obtained by extending the single-layer network characteristics indicators and used in the Shanghai public transportation network. The results of each indicator are shown in Table 1.

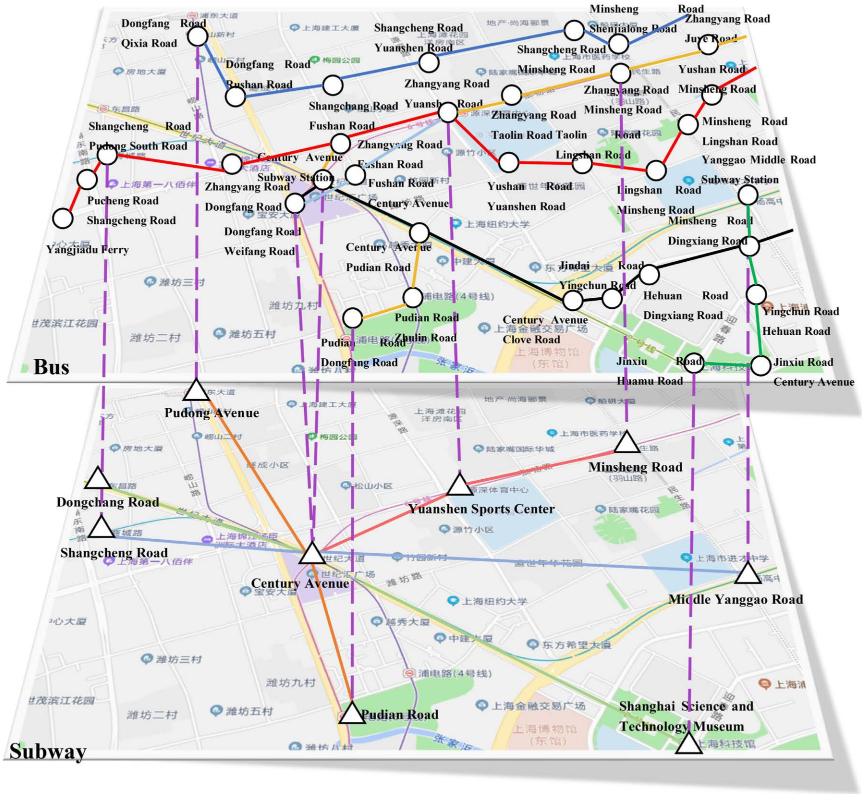


Figure 3. Partial schematic diagram of shanghai bus-subway dual-layer network.

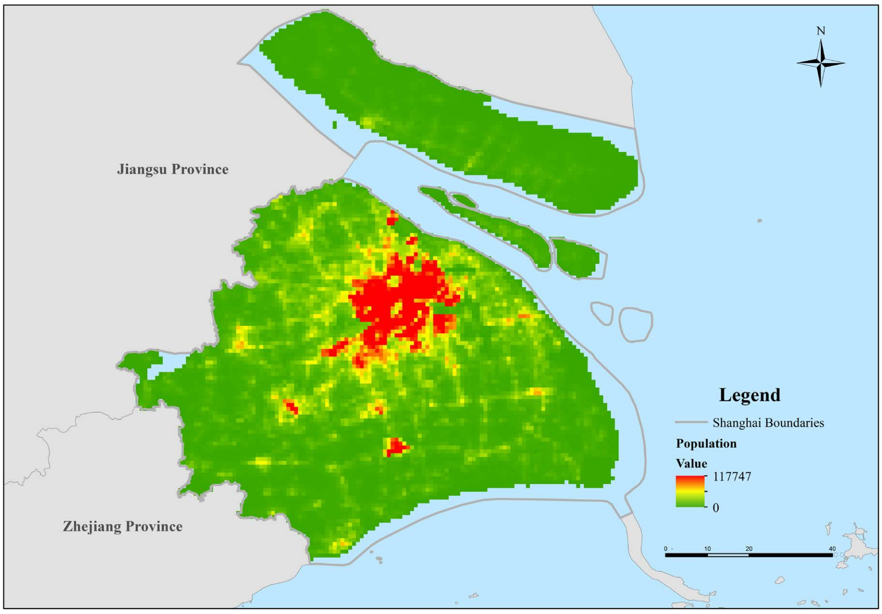


Figure 4. Population kilometer grid distribution map.

Table 1. Topology table of shanghai public transportation network.

	Average degree	Clustering coefficient	Diameter	Feature path length
Subway	2.307^{a}	0.0090	48	16.29
Bus	2.800	0.0678	78	22.99
Bus-subway	2.919	0.0693	67	20.69

1) Degree and degree distribution

From **Table 1**, the average degree of the bus-subway dual-layer network is 2.919, which is higher than the average degree of the subway and bus sub-networks (2.307 and 2.800, respectively), indicating that each station is directly connected to about three other stations on average. The higher the average degree, the better the network's connectivity, which laterally indicates that the dual-layer network increases the connectivity of the transportation network to some extent compared to the two separate networks of bus and subway. In the degree distribution, the degrees of the three networks of subway, bus, and bus-subway are mainly concentrated around 1 - 5, showing a trend that low-degree nodes are dominant and high-degree nodes are less. There are 368 points with degree values below 5 in the subway network, accounting for 97.35% of the total nodes. 11,877 points with degree values below 5 in the bus network, accounting for 93.52%, and 10,978 points below 5 in the bus-subway network, accounting for 79.63% of the real purpose. There are very few nodes with large degree values, which have apparent intermittent dispersion characteristics. The maximum degree value of the subway network is 8, and only one is the Century Avenue station. Only 38 nodes with a degree value above ten accounts for 0.34% of the total number of nodes in the public transportation network. The bus-subway network has 187 points with a degree value of 10 or more, accounting for 1.3% of the total nodes. It indicates that the degree distribution of nodes is highly uneven. Less than 1% of the bus and subway sub-networks nodes have a degree value greater than 10. The degree values only improve after the bus network is embedded in the subway network to form a multi-layer network. Overlaying the population heat map with the top 1% of nodes (Figure 5) shows that these points tend to be densely populated stations in the city, in prime locations, and have certain geographical advantages.

Using the cumulative degree distribution formula for the bus, subway, and bus-subway networks, the probability plot of the cumulative distribution of node degrees is obtained, as shown in Figure 6. From the figure, the degree distributions of the subway, bus, and bus-subway networks span in increasing order. In the power function fit, only $\gamma \in (2,3)$ in the bus network, conforms to the standard BA model power law. As a result, the bus network in Shanghai has scale-free network characteristics in L-space. Since the scale-free network has strong fault tolerance, according to the growth and merit selectivity of a scale-free network, when new subway or bus lines are added in the future, the new stations can be considered to be connected with the original stations with high degree values, so as to evolve and obtain scale-free network, thus improving the safety of the whole transportation system.

2) Feature path length and clustering coefficient

According to the results in Table 1, the characteristic path lengths of the subway, bus, and bus-subway dual-layer networks are 16.29, 22.99, and 20.69, respectively. In contrast, the characteristic path lengths of the bus and bus-subway multi-layer

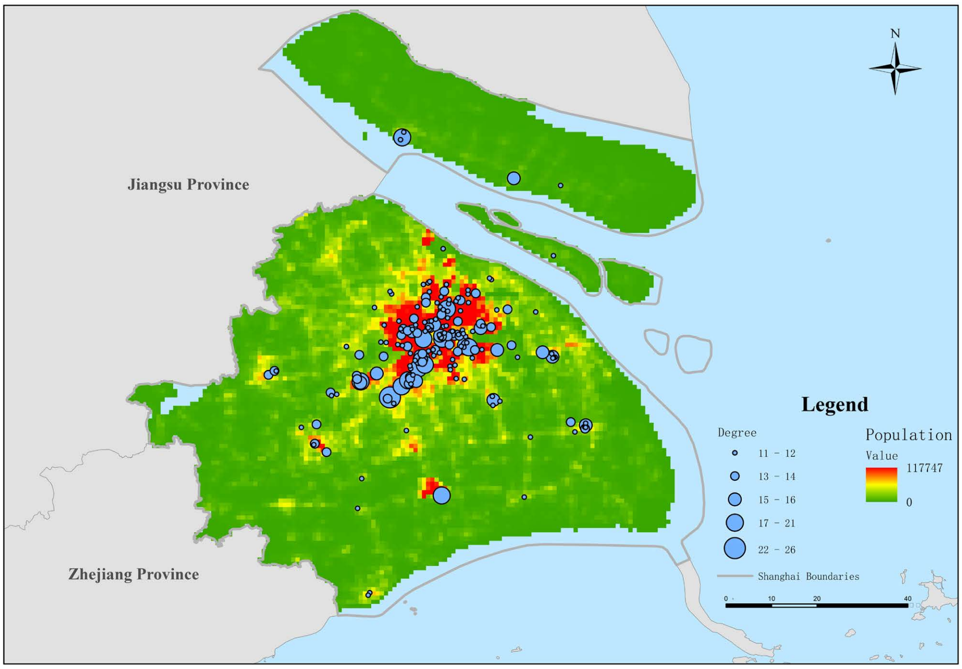


Figure 5. The degree distribution of the top 1% stations of Shanghai bus-subway dual-layer network under the background of population heat.

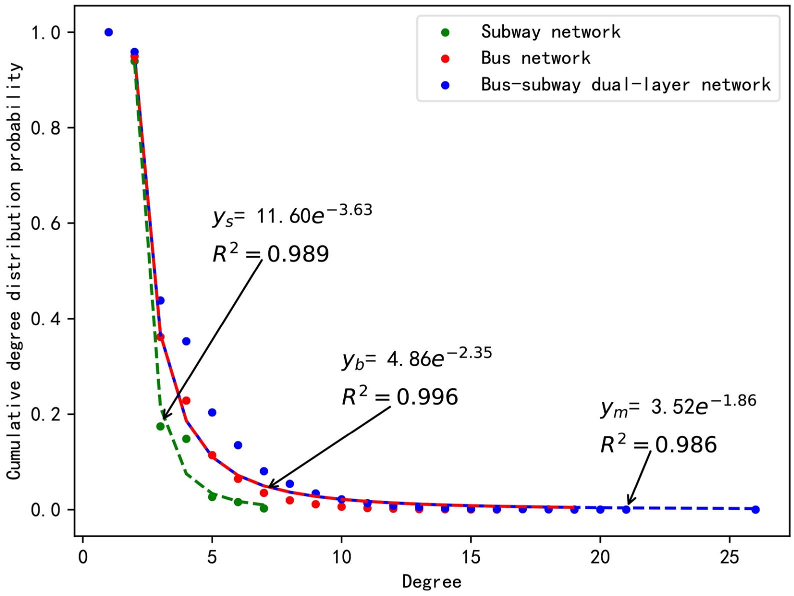


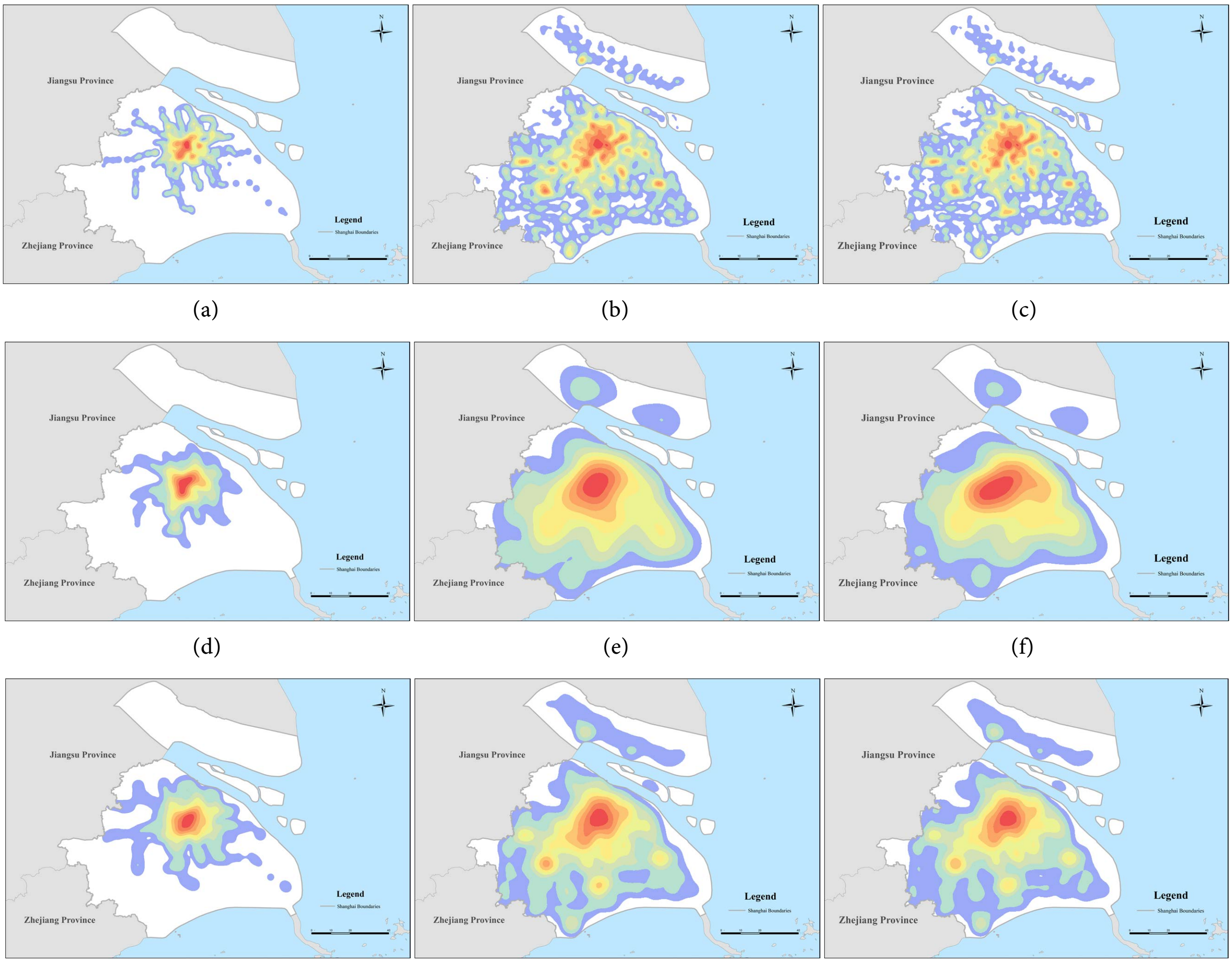
Figure 6. Node degree cumulative distribution probability.

networks are similar, indicating an average of 20 stops between any two stations in the public transportation system. The feature path lengths decrease after embedding the subway network into the bus network. Among the three networks, the subway network has a minor diameter of 48, followed by the bus-subway network with a diameter of 67, and finally, the bus network with a diameter of 78. It means the longest distance between any two subway stations is 48 stations, while the longest distance between bus stations is 78 stations. There is a significant reduction in the network diameter when considering bus-subway interchange, indicating that the interconnection between bus and subway helps to improve the network's accessibility.

In a public transportation network, the clustering coefficient can portray the closeness of the sites connected in the network. Most of the stations' neighboring stations are on the same line in L-space, so most stations have zero clustering coefficients. Only a few stations have non-zero clustering coefficients, which makes the average clustering coefficient of the network small. Given the information in Table 1, the poor clustering coefficients of all three networks suggest that the topological space's network connections still need to be improved. The clustering coefficients in the bus-subway multi-layer network are still somewhat higher than in the single-bus network, indicating that the multi-layer network can, to some extent, boost network proximity and facilitate travel.

3.2. The Statistical and Spatial Heterogeneity of Nodal Centralities

The degree centrality, betweenness centrality, and closeness centrality for bus, subway, and bus-subway multi-layer networks are calculated, and the bridging effect and accessibility are analyzed. The most significant areas and areas needing development are found, and their spatial distribution is visualized as a heat map, as shown in Figure 7.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 7. Heat map of centrality spatial distribution of shanghai public transportation network. (a) Subway network degree centrality; (b) Bus network degree centrality; (c) Dual-layer network degree centrality; (d) Subway network betweenness centrality; (e) Bus network betweenness centrality; (f) Dual-layer network betweenness centrality; (g) Subway network closeness centrality; (h) Bus network closeness centrality; (i) Dual-layer network centrality.

1) Subway network

From Figure 7, it can be obtained that the degree centers of the subway network show significant spatial heterogeneity characteristics. The higher degree points are usually located in the central urban areas with more dense population distribution and more developed economies, such as Xuhui District and Huangpu District. The betweenness centrality of the subway network has a more obvious circle structure in space and shows a decreasing distribution from the center to the outside. Compared with the heat distribution map of degree centrality, the high value of betweenness centrality is more concentrated in the central city, and less space is extended outward. It is because the betweenness centrality focuses on the traffic load of the nodes, while the subway network mainly covers the central city. The further outward, the fewer stations there are. So the probability that the shortest distance between the peripheral stations and other stations must go through the station is lower, resulting in generally lower betweenness centrality in the peripheral areas. Sites with high betweenness centrality tend to bear high traffic flow, primarily in the central city, critical intersections, mainly in Xuhui District, Jing'an District, etc.

Compared with betweenness centrality, closeness centrality distribution tends to extend outward along the distribution of subway stations, covering the most expansive area among the three. At the same time, the spatial differentiation shows an obvious *core-edge* pattern. The central stations with closeness centrality value have significant aggregation characteristics, forming a core circle in the central city, mainly in Xuhui District, Huangpu District, Putuo District, Jing'an District, and Hongkou District. The peripheral stations in the central city are less interrelated, such as Jiading District, Qingpu District, Songjiang District, etc., which become the edges of the entire network accessibility. Thus the closeness centrality of the entire subway network shows a *core-edge* circle structure. The spatial layout is also determined by the nature of the proximity centrality itself, which is mainly used to portray the accessibility of the network, as the subway network in Shanghai has a structure of radiation from the center to the surroundings. In order to enhance the accessibility between districts, new circular lines can be built in the planning of metro lines to increase the connectivity of outer circles.

2) Bus network

The high centers of the public transportation network form a discontinuous island structure in spatial distribution, most of which are located in the city's central area. The high-value areas show a clustering structure, while the low-value areas show a fragmented structure, and the overall performance is mosaic distribution. Unlike the single-center structure of the degree centrality heat map of the subway network, the degree centrality heat map of the bus network shows a multi-center structure. Each administrative district has high-value areas, such as Hongqiao Airport in Minhang District and Renmin North Road in Songjiang District. These areas have commonalities, such as relatively dense populations and landmark locations in the corresponding administrative districts. While the low-value areas are fragmented but cover the entire of Shanghai, which is consistent with the characteristics of the high coverage of the bus network.

Similar to the distribution of subway betweenness centrality, the betweenness centrality of the bus network shows a circle structure spreading from the center to the surrounding area. The high-value areas are concentrated in the central urban areas represented by Xuhui, Huangpu, Hongkou, and Jing'an districts. The middle and low-value areas show a *claw* structure, extending more widely in the southeast, south, and southwest directions of Shanghai. Stations with high values are usually heavily loaded and are often located in the economic and political centers of the region. The transportation facilities network is also more well-developed than in the low-value areas, and they bear the heavy responsibility of serving the outer circle and have a more significant potential for traffic convergence. The *claw*-type sites in the low and medium-value areas are mainly located in Songjiang District, along Minhang District - Fengxian District, and Pudong New Area. In the heat distribution of the population, these three areas have a high density of population distribution. There are a number of neighborhoods, schools, and other residential lands. This layout suggests that the planning of bus routes needs further to strengthen the deployment of routes in these areas to connect the central city with the non-central city and spread the high load in the central city.

In the heat distribution map of closeness centrality, a polycentric structure appears. Moreover, the main center is still located in the central area of the city, the sub-center is located in Songjiang District, and there are three other sub-centers located in Qingpu District, Fengxian District, and Pudong New Area, which is roughly in line with the betweenness centrality distribution. The closeness centrality mainly portrays the accessibility difficulty between stations. The more aggregated between stations, the higher the value. The distribution of the closeness centrality of the bus station can be seen in the main urban area is densely distributed, so the degree of accessibility in this area is high. At the same time, bus stations in Qingpu District, Fengxian District, and Pudong New Area also show aggregation. So outside the main urban area appears, several sub-centers. These sub-centers are mainly located near the governments of the administrative districts and have relatively concentrated population distribution, which increases the accessibility level of non-main urban areas within a short distance and small area. However, the closeness centrality between the central city and the non-main city is still low, indicating that there is still room for further planning of transit links between the central city and the non-main city.

3) Bus-subway dual-layer network

The centrality of the dual-layer network reflects the synergy and integration effect of the bus and subway networks and often reveals the area where the cohesiveness of the whole urban transportation system structure plays the most central role. The stations in such areas should be maintained with an emphasis on traffic management, and traffic resources should be reasonably allocated from traffic planning. The centrality distribution of the dual-layer network is very similar to that of the bus network, showing a structure of high-value clustering and low-value fragmentation in terms of degree centrality distribution. The degree distribution of the dual-layer network does not change much in space, and the degree values only change at bus stops with subway interchanges.

There is a claw structure in the distribution of betweenness centrality of bus-subway dual-layer network, just like the bus network. However, there are still some differences in the centrality distribution between these two networks. For example, in the distribution of betweenness centrality in the dual-layer network, the extension direction of the third and fourth circles is changed from the original southward to the southeastward. The coverage area of the fifth circle, represented by the middle-value circle, is significantly increased, and the coverage area of the eighth circle, represented by the low-value circle, is reduced. It indicates that after considering the subway stations, the connection between the central urban areas of the whole public transportation network is strengthened, making the spatial distribution of high median stations more concentrated in the center of Shanghai, highlighting the economic core status of the circle area. However, the bridging effect between the southern administrative districts of Shanghai, represented by Songjiang and Minhang districts, and the city center has a clear tendency to weaken, which can be tilted to the south to a certain extent in the metro planning. In addition, there are many universities and colleges in Yangpu District and Pudong New Area, and the flow of people is relatively large. The distribution of the heat map of the betweenness centrality of the dual-layer network tends to tilt to the east, while the betweenness centrality value of the single-layer bus network in the area is not high. It shows that the synergy of bus and subway stations in this area can better load the high traffic volume in the region and reshape the location importance of the transportation network through the synergy and complementary effect of multiple transportation modes. It can be used as a model for the collaborative planning of bus and subway lines in other regions

The bus-subway dual-layer network still shows a polycentric structure in the heat distribution of closeness centrality, with no significant changes in the spatial distribution of the high-value areas, but it increases the coverage of the medium-value areas and decreases the range of the low-value ones. This is due to the small coverage area of the subway, which is the core of the central city and is distributed radially in all directions. The aggregation within the area increases when there is a subway station near the bus stop. It can be seen that the dual-layer network makes the whole transportation network more convergent to the area covered by the subway. Therefore, while considering convenient bus and subway interchange, more bus stops should be deployed in areas not covered by subway stations to increase the accessibility between regions.

To further demonstrate the differences among the networks, the top 10 centrality values for the bus network and the bus-subway network are presented in Tables 2-4. From the data in Table 2, it can be seen that the ranking of the degree centers in the top 10 changes slightly in both networks, except Xinzhuang, which is ranked first and remains unchanged. The ranking of all other stations increases and decreases, and the degree centrality values of the multi-layer bus-subway network increase significantly compared to the values of the single bus network. Xinzhuang is not geographically located in the center of Shanghai, but it is surrounded by many houses, companies, and schools and has a high flow of people and a high degree of connectivity to transportation nodes. Xinzhuang subway station has two subway lines, Line 1 and Line 5, which further increases the degree value of this station. The station's top ten bus network degree value is located in the Huangpu, Hongkou, Xuhui, and other central areas of Shanghai, such as the Shanghai Stadium, Jing'an Temple, etc. This part of the station is usually located in Shanghai's landmark location. A few stations are in non-central areas, such as Xinzhuang, Lotus Road subway station, and Nanqiao bus station. The location of these stations is located in areas with a large flow of

Table 2. Degree centrality table.

Bus network		Bus-subway network	
Station	Degree centrality	Station	Degree centrality
Xinzhuang	19	Xinzhuang	26
Dongmen	16	Jing'an Temple	21
Lotus Road Subway Station	16	Lotus Road Subway Station	20
Jing'an Temple	15	Shanghai Gymnasium	19
Shanghai Gymnasium	15	Caohejing	18
Huaihai East Road, Xizang South Road	15	Dongfang Road Lancun Road	18
Huting North Road Hussong Highway	14	Longhua	18
Nanbao Town	14	Pu Jian Road South Yang Gao Road	18
Nanqiao Bus Station	14	Huaihai East Road, South Xizang Road	18
Pu Jian Road South Yang Gao Road	14	Dongmen	17

Table 3. Betweenness centrality table.

Bus network		Bus-subway network	
Station	Betweenness centrality	Station	Betweenness centrality
Hongqiao West Traffic Center	0.210	Hongqiao West Traffic Center	0.182
Rongle Road North People's Road	0.166	Rongle Road North People's Road	0.142
Shanghai Gymnasium	0.113	Hongqiao Terminal 2	0.134
Lotus Road Subway Station	0.087	Hongqiao Terminal 1	0.134
Wenshui Road Republican Xin Road	0.074	Shanghai Zoo	0.123
Farmers' Market	0.071	Terminal 2	0.093
Terminal 2	0.071	Wenshui Road Republican Xin Road	0.090
Tianshan Road, West Zhongshan Road	0.069	Wuzhou Avenue Subway Station	0.079
Hangtou	0.067	Xinchang	0.076
Nanqiao Bus Station	0.065	Shanghai Gymnasium	0.072

Table 4. Closeness centrality table.

Bus network		Bus-subway network	
Station	Closeness centrality	Station	Closeness centrality
Rongle Road North People's Road	0.0667	Hongqiao Terminal 2	0.0770
Hongqiao West Transportation Center	0.0664	Terminal 2	0.0768
Shanghai Gymnasium	0.0660	Hongqiao Terminal 1	0.0767
North Caoxi Road Yu De Road	0.0644	Hongqiao West Transportation Center	0.0765
Yishan Road, West Zhongshan Road	0.0643	Shanghai Zoo	0.0761
Terminal 2	0.0643	Rongle Road North People's Road	0.0757
Zhaojiabang Road Tianping Road	0.0641	Hongqiao Railway Station	0.0752
Dapu Bridge	0.0639	Wujiaxiang	0.0737
Nanqiao Bus Station	0.0637	Wenshui Road Republican Xin Road	0.0736
Minle District	0.0635	Shanghai Gymnasium	0.0735

people. In the bus-subway dual-subway network, the top ten stations in terms of spatial location are shifted to the southwest towards Minhang District, basically located along Line 1. There are two or more interchange lines at several subway stations on Line 1, increasing the degree value of stations in this part of the city, which makes a significant change in the degree value order of the whole network. This highly centralized shift in the dual-layer network of Shanghai's Line 1, which passes through several high-traffic stations, has dramatically improved the external connections of the area and is conducive to improving the efficiency and service quality of the integrated public transportation system.

From the data in **Table 3**, the rank order of the top 10 stations of betweenness centrality does not change much. The top two stations of the dual-layer network are consistent with the bus network. After considering the interchange role of the subway network, the third, fourth, and fifth places are replaced by metro stations Hongqiao Terminal 2, Hongqiao Terminal 1, and Shanghai Zoo. At the same time, the bus station Terminal 2, Wenshui Road Republican New Road, Wuzhou Avenue metro station order has also been improved, which makes the Shanghai Gymnasium bus station from the original third place down to tenth place. From the location distribution, the bus network betweenness centrality is located in the top 10 stations are more scattered. The distribution pattern can be summarized into two categories. The first category is located near the junction between the administrative regions for critical intersections to assume the role of intermediary passenger convergence, such as Hangzhou and Farmers' Markets. The second category is located in the center of the administrative district, usually for the population gathering area, often for the huge load-bearing sites, such as the Shanghai Stadium and Hongqiao West Transportation Center. The betweenness centrality near Hongqiao Airport increases significantly in the bus-subway dual-layer network. Several bus and subway stations near Hongqiao Airport have risen to the top 10. As the transportation hub of Shanghai, the Hongqiao area serves as a bridge to other regions, and the increased betweenness centrality of the area is conducive to improving the connectivity between Shanghai and other cities within the city. In addition, the jump in the order of Wuzhou Avenue metro station and Xinchang location in the bus-subway network makes the distribution of high betweenness centrality values more balanced throughout Shanghai. This balanced distribution can improve the traffic flow convergence potential of the network on a larger scale.

It is noticed in **Table 4** that the rank order of closeness centrality varies significantly between the two networks. The top 10 stations in closeness centrality for the bus network are mainly located in the central city, such as Cao Xi North Road, Yude Road, Zhongshan West Road, Yishan Road, and Dapu Bridge etc. In addition, some non-central city areas with high population concentration and high pedestrian flow also have high closeness centrality. In the bus-subway network, the closeness centrality value of the Hongqiao Airport area is significantly increased. For example, Hongqiao Terminal 2, Terminal 2, Hongqiao Terminal

1, and Hongqiao West Transportation Center jump to the top four positions. The relatively dense subway and bus lines in the area make it possible to consider the interaction of the two networks simultaneously, considerably improving the ranking of stations in the area. In addition, among the three centralities, the bus-subway dual-layer network increases the centrality value compared to the bus single-layer network. It shows that when the two networks interact, their structural properties change significantly, and considering multi-layer networks is a necessary paradigm for further study of complex networks.

4. Conclusions and Discussions

Multi-layer networks break through the traditional single-layer network node and edge homogeneity and provide a new perspective for studying the structural characteristics of urban public transportation systems. This paper takes Shanghai as an example and abstracts the bus and subway in the public transportation system into two types of nodes and considers the connected edge relationship within and between layers to establish a two-layer topological network model. Based on the theory of multi-layer networks, the structural characteristics of the Shanghai public transportation system are more intuitively portrayed. The study results find that the bus-subway dual-layer network has a greater average degree compared to the bus and subway sub-networks, which increases the network's connectivity at a specific layer level. The construction of the subway network helps the bus network break through the spatial constraints in terms of the physical structure and allows for more diverse connections between bus stops. The subway network's spatial distribution is relatively sparse, and its central heat distribution is limited to a small area of the central city. The degree of centrality of high-value stations of bus and dual-layer networks is primarily in relatively densely populated areas. For betweenness centrality, bus, and dual-layer networks show a circle structure spreading from the center to the surrounding area. The node closeness centrality values of single and dual-layer networks show a polycentric structure and a tendency to converge toward the city center.

In this paper, only two types of transportation networks, bus and subway are considered. In the future, the characteristics of more extensive scale and more types of transportation networks can be considered. The correlation between the structural characteristics of multi-layer networks and network efficiency and urban spatial patterns is also a direction worth exploring. In addition, the analysis of spatial coupling and spatial differentiation regarding bus stop density, connectivity, and transfer convenience is critical. It is also essential to evaluate the bus-subway interchange's spatial efficiency and social equity by combining POI data of employment and residence, population distribution data, etc. Furthermore, the simulation of bus-subway network operation demand and optimization design is another aspect worth exploring. This simulation can be carried out according to the land use evolution under different development scenarios.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] De Bona, A.A., de Oliveira, R.M., Fonseca, K.V.O. and Lüders, R. (2021) A Reduced Model for Complex Network Analysis of Public Transportation Systems. *Physica A*: *Statistical Mechanics and Its Applications*, **567**, Article 125715. https://doi.org/10.1016/j.physa.2020.125715

[2] Dai, L., Derudder, B. and Liu, X. (2018) The Evolving Structure of the Southeast Asian Air Transport Network through the Lens of Complex Networks, 1979-2012. *Journal of Transport Geography*, **68**, 67-77. https://doi.org/10.1016/j.jtrangeo.2018.02.010

[3] Jiao, J., Wang, J., Jin, F. and Du, C. (2016) Understanding Relationship between Accessibility and Economic Growth: A Case Study from China (1990-2010). *Chinese Geographical Science*, **26**, 803-816. https://doi.org/10.1007/s11769-016-0831-0

[4] Wang, L., Wang, K. and Shen, J. (2020) Weighted Complex Networks in Urban Public Transportation: Modeling and Testing. *Physica A*: *Statistical Mechanics and Its Applications*, **545**, Article 123498. https://doi.org/10.1016/j.physa.2019.123498

[5] Zhang, J., Wang, S. and Wang, X. (2018) Comparison Analysis on Vulnerability of Metro Networks Based on Complex Network. *Physica A*: *Statistical Mechanics and Its Applications*, **496**, 72-78. https://doi.org/10.1016/j.physa.2017.12.094

[6] Chen, J., Liu, J., Peng, Q. and Yin, Y. (2022) Resilience Assessment of an Urban Rail Transit Network: A Case Study of Chengdu Subway. *Physica A*: *Statistical Mechanics and Its Applications*, **586**, Article 126517. https://doi.org/10.1016/j.physa.2021.126517

[7] Latora, V. and Marchiori, M. (2002) Is the Boston Subway a Small-World Network? *Physica A*: *Statistical Mechanics and Its Applications*, **314**, 109-113. https://doi.org/10.1016/S0378-4371(02)01089-0

[8] Soh, H., *et al.* (2010) Weighted Complex Network Analysis of Travel Routes on the Singapore Public Transportation System. *Physica A*: *Statistical Mechanics and Its Applications*, **389**, 5852-5863. https://doi.org/10.1016/j.physa.2010.08.015

[9] Sienkiewicz, J. and Hołyst, J.A. (2005) Statistical Analysis of 22 Public Transport Networks in Poland. *Physical Review E*, **72**, Article 046127. https://doi.org/10.1103/PhysRevE.72.046127

[10] Tsigdinos, S., Paraskevopoulos, Y., Tzouras, P., Bakogiannis, E. and Vlastos, T. (2023) Rethinking Road Network Hierarchy towards New Accessibility Perspectives. *Transportation Research Procedia*, **69**, 195-202. https://doi.org/10.1016/j.trpro.2023.02.162

[11] Bombelli, A., Santos, B.F. and Tavasszy, L. (2020) Analysis of the Air Cargo Transport Network Using a Complex Network Theory Perspective. *Transportation Research Part E*: *Logistics and Transportation Review*, **138**, Article 101959. https://doi.org/10.1016/j.tre.2020.101959

[12] Yiqiao, W., Xianbin, C., Fangyun, Q. and Lu, C.T. (2022) Vulnerability Analysis of the Chinese Coupled Aviation and High-Speed Railway Network. *Chinese Journal of Aeronautics*, **35**, 189-199. https://doi.org/10.1016/j.cja.2022.01.009

[13] Liu, C. and Duan, D. (2020) Spatial Inequality of Bus Transit Dependence on Urban Streets and Its Relationships with Socioeconomic Intensities: A Tale of Two Megac-

ities in China. *Journal of Transport Geography*, **86**, Article 102768. https://doi.org/10.1016/j.jtrangeo.2020.102768

[14] Alderson, D.L., Funk, D. and Gera, R. (2020) Analysis of the Global Maritime Transportation System as a Layered Network. *Journal of Transportation Security*, **13**, 291-325. https://doi.org/10.1007/s12198-019-00204-z

[15] De Domenico, M. (2022) Multilayer Networks: Analysis and Visualization: Introduction to muxViz with R. Springer Nature, London, UK. https://doi.org/10.1007/978-3-030-75718-2

[16] Interdonato, R., Magnani, M., Perna, D., Tagarelli, A. and Vega, D. (2020) Multilayer Network Simplification: Approaches, Models and Methods. *Computer Science Review*, **36**, Article 100246. https://doi.org/10.1016/j.cosrev.2020.100246

[17] Bianconi, G. (2018) Multilayer Networks: Structure and Function. Oxford University Press, Oxford. https://doi.org/10.1093/oso/9780198753919.001.0001

[18] De Domenico, M., Solé-Ribalta, A., Omodei, E., Gómez, S. and Arenas, A. (2015) Ranking in Interconnected Multilayer Networks Reveals Versatile Nodes. *Nature Communications*, **6**, Article No. 6868. https://doi.org/10.1038/ncomms7868

[19] Solé-Ribalta, A., De Domenico, M., Gómez, S. and Arenas, A. (2016) Random Walk Centrality in Interconnected Multilayer Networks. *Physica D*: *Nonlinear Phenomena*, **323-324**, 73-79. https://doi.org/10.1016/j.physd.2016.01.002

[20] De Bacco, C., Power, E.A., Larremore, D.B. and Moore, C. (2017) Community Detection, Link Prediction, and Layer Interdependence in Multilayer Networks. *Physical Review E*, **95**, Article 042317. https://doi.org/10.1103/PhysRevE.95.042317

[21] Huang, X., Chen, D., Ren, T. and Wang, D. (2021) A Survey of Community Detection Methods in Multilayer Networks. *Data Mining and Knowledge Discovery*, **35**, 1-45. https://doi.org/10.1007/s10618-020-00716-6

[22] Alessandretti, L., Orozco, L.G.N., Saberi, M., Szell, M. and Battiston, F. (2022) Multimodal Urban Mobility and Multilayer Transport Networks. *Environment and Planning B*, 1-33. https://doi.org/10.1177/23998083221108190

[23] De Domenico, M., Nicosia, V., Arenas, A. and Latora, V. (2015) Structural Reducibility of Multilayer Networks. *Nature Communications*, **6**, Article No. 6864. https://doi.org/10.1038/ncomms7864

[24] Rhoads, D., Solé-Ribalta, A., González, M.C. and Borge-Holthoefer, J. (2020) Planning for Sustainable Open Streets in Pandemic Cities. *Communications Physics*, **4**, Article No. 183. https://doi.org/10.1038/s42005-021-00688-z

[25] Szell, M., Mimar, S., Perlman, T., Ghoshal, G. and Sinatra, R. (2022) Growing Urban Bicycle Networks. *Scientific Reports*, **12**, Article No. 6765. https://doi.org/10.1038/s41598-022-10783-y

[26] Ding, R., Ujang, N., Hamid, H.B., Manan, M.S.A., He, Y., Li, R. and Wu, J. (2018) Detecting the Urban Traffic Network Structure Dynamics through the Growth and Analysis of Multi-Layer Networks. *Physica A*: *Statistical Mechanics and Its Applications*, **503**, 800-817. https://doi.org/10.1016/j.physa.2018.02.059

[27] Boccaletti, S., *et al.* (2014) The Structure and Dynamics of Multilayer Networks. *Physics Reports*, **544**, 1-122. https://doi.org/10.1016/j.physrep.2014.07.001

[28] Feng, S., Xin, M., Lv, T. and Hu, B. (2019) A Novel Evolving Model of Urban Rail Transit Networks Based on the Local-World Theory. *Physica A*: *Statistical Mechanics and Its Applications*, **535**, Article 122227. https://doi.org/10.1016/j.physa.2019.122227