Journal of Highway and Transportation Research and Development
2024, 18(3): 17−25

Research Article
ISSN 2095−6215
DOI: 10.26599/HTRD.2024.9480018

Accessibility of urban agglomeration integrated passenger transport network considering travel impedance

Chengbing Li[1*], Peng Wu[2], Yunfei Li[2]

1. *School of Transportation, Inner Mongolia University, Hohhot, Inner Mongolia 010070, China*;
2. *School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China*

Abstract: To clarify the multi-layer spatial structure of urban agglomeration integrated passenger transport networks and enhance their functional attributes, a new model is proposed that considered urban transport transfer from a novel perspective of coupling. The impedance accessibility of the network is analyzed in terms of travel cost and time. Firstly, the highway subnet and the railway subnet are constructed using the Space-P modeling method from complex network theory. Passenger stations within the urban agglomeration are represented as nodes in the network and are assigned numerical identifiers. The edge weights are calibrated based on travel time and fare. Secondly, the central urban area of each city within the urban agglomeration is designated as a traffic district. Coupling edges are added between nodes connected by urban public transport, walking, or other transfer modes to create coupling subnets. Thirdly, the highway and railway subnets are integrated into a comprehensive network through these coupling subnets. The traditional network efficiency index is refined to develop a weighted impedance efficiency index, which evaluates the accessibility of nodes and networks. Finally, using the Chengdu-Chongqing urban agglomeration as a case study, the results indicate that: (1) the coupling of multiple nodes enchances the impedance accessibility of these nodes, demonstrating that urban transport transfers are a crucial factor in the study of integrated passenger transport network; (2) compared to the highway subnet and the railway subnet, the impedance accessibility of the integrated network improves by 83.4% and 28.5%, respectively, indicating that the coupling of highway and railway passenger subnets significantly enhances the impedance accessibility of the urban agglomeration passenger transport network; (3) promoting the coupling and coordination between stations or across multiple transportation modes is essential for reducing travel costs and time for passengers, thereby facilitating the development of a more convenient integrated passenger transport network within urban agglomerations.

Keywords: traffic engineering; accessibility; complex network; integrated passenger transport network; urban agglomeration; travel impedance

1 Introduction

The Outline of Building a Strong Transportation Country (in China) clearly states that it is necessary to build a convenient and smooth integrated transport network in urban agglomeration to lay a solid foundation for a country with a strong transportation system. With the development of economy and society and the acceleration of urbanization in China, the urban agglomeration as the main area of regional population, economy and industry, the communication between inner cities becomes more and more frequent. Therefore, people urgently need a passenger transport network with better accessibility and lower travel cost and time in urban agglomeration. So, a more realistic model of urban agglomeration integrated passenger transport network should be constructed, and the accessibility of the network should be studied to improve the convenience of inter-city travel and to support the development of regional economy and society.

So far, the complex network theory has been widely used in transportation networks. For example, Candelieri, et al.[1] modeled the public transportation network and analyzed its vulnerability based on graph theory and to-

Received: 21 August 2023; **Revised:** 13 December 2023; **Accepted:** 13 January 2024

* *E-mail address*: bingbingnihao2008@126.com

pological approach. Wang, et al.[2] constructed the bus transit network model based on Space-L modeling method and studied the detour optimization scheme for failure of transit station. Lu, et al.[3] evaluated the vulnerability of rail transit network by considering the actual passenger flow, user travel time, and bus connection efficiency based on the topology of ra8 op[l transit network. Feng, et al.[4] built the undirected weighted aviation network model, and analyzed its topology structure and its robustness considering node failure and edge failure. Wei, et al.[5] built the urban composite traffic network model combining urban road traffic network and urban rail transit network, and analyzed the accessibility characteristics of the network. These related studies mainly focus on bus transit, rail transit, urban road, aviation network, etc., with abundant research.

Some scholars have also applied the complex network theory to the urban agglomeration passenger transport network. Ji, et al.[6] established a method for extracting the spatial structure of highway passenger transport network in urban agglomeration based on complex network theory. Li, et al.[7] superimposed the road traffic network and railway traffic network of urban agglomeration to form the urban agglomeration composite traffic network from a composite perspective and analyzed its topological structure. However, this composite method ignores the influence of urban traffic transfer coupling. Moreover, some scholars continue to deepen the network topology space structure, and then consider the functional attributes of the network. For example, Mao et al.[8] proposed a method for calculating the importance degree of comprehensive nodes in urban agglomeration, considering the basic economic attribute, network topology attribute, and urban connection strength attribute. Li, et al.[9] improved the load distribution model based on the actual passenger flow and evaluated the invulnerability of the urban agglomeration composite transportation network. Zhang, et al.[10] evaluated the economic, social and ecological impacts of the Beijing-Tianjin-Hebei urban agglomeration transportation network from the perspective of sustainability. Guo, et al.[11] adopted spatial syntax to evaluate the topology of road network and the traffic control strength of node cities in Beibu Gulf urban agglomeration. Some scholars have put forward some prospects for the deficiency of research on the structural attribute and functional attribute of network. Xiao, et al.[12] discussed the attribute influencing factors of intercity passenger transport network, and believed that "attribute index" and "network index" needed to be further connected. Guan, et al.[13] considered that it is necessary to strengthen the research on the theoretical and methodological system of integrated transportation network system engineering, and the complex characteristics of multi-layer integrated transportation network structure is one of the important research fields of transportation network system engineering.

In terms of the accessibility evaluation of transportation networks, Koenig[14] believes that accessibility refers to the difficulty of reaching a certain place in a certain transportation system. Aklilu, et al.[15] used spatial data to analyze the accessibility of the Addis Ababa light rail. Wang, et al.[16] used the cost-weighted distance method to calculate the spatial accessibility of counties (cities, districts) in China, and explored the relationship between traffic accessibility and population aggregation. In terms of the accessibility evaluation of urban agglomeration passenger transport network, Zong, et al.[17] used weighted average travel time, economic potential index and other indicators to analyze the impact of high-speed rail on the accessibility of Chengdu-Chongqing urban agglomeration counties. Xu, et al.[18] proposed a method for measuring the accessibility of urban agglomeration under highway traffic and highway connecting with other modes of transportation from the perspective of travel time. Hong, et al.[19] used the weighted average travel time and accessibility coefficient to measure the accessibility of regional transportation network. In these studies, the accessibility value of a node represents the average of the shortest distance or shortest time from the node to all other nodes, which is similar and inversely related to the network efficiency index in complex network theory. And most of these studies are based on distance, time, population, economy and other factors, rarely considering the cost factor. Some of these studies analyze the accessibility between cities without constructing a more detailed passenger transport network.

In summary, the multi-layer spatial structure of urban agglomeration integrated passenger transport network is not perfect, and the urban agglomeration composite transport network model does not consider the impact of urban transport transfer. So, more in-depth analysis of the structural attribute and accessibility of urban agglomeration integrated passenger transport network is required. Here the model of urban agglomeration integrated passenger transport network with multi-layer combination of passenger transport subnets and coupling subnets is established from the coupling perspective, which is closer to the actual situation. Moreover, the accessibility of urban agglomeration integrated passenger transport network is evaluated from the perspective of richer network functional attributes by considering the inter-city travel impedance, time and cost.

2 The model of urban agglomeration integrated passenger transport network

2.1 The passenger subnet

The long-distance bus stations in the urban agglomeration are abstracted as nodes in the network and numbered, and the node number set of highway passenger subnet $V_1=\{1,2,3,\cdots,n_1\}$ is constructed, where n_1 denotes the number of highway nodes. According to the Space-P[20] modeling method, as long as a direct single ticket can be purchased between two stations, there is a connecting edge. The highway subnet adjacency matrix $\boldsymbol{B}=(b_{ij})_{n_1\times n_1}$ is constructed. If there is a direct ticket between node i and node j, then $b_{ij}=1$, if not, then $b_{ij}=0$. The lowest fare between two stations is recorded, so that the highway subnet fare matrix $\boldsymbol{B}^{\text{fare}}=(b_{ij}^{\text{fare}})_{n_1\times n_1}$ is constructed. Since the specific travel time of highway passenger transport is difficult to query, the travel time between stations is evaluated according to the transport speed and distance between stations, so that the highway subnet time matrix $\boldsymbol{B}^{\text{time}}=(b_{ij}^{\text{time}})_{n_1\times n_1}$ is constructed. The fare matrix or time matrix is taken as the edge weight matrix, that is, the weighted adjacency matrix.

The railway stations for passenger service in urban agglomeration are abstracted as nodes in the network and numbered, and the node number set of railway passenger subnet $V_2=\{n_1+1,n_1+2,\cdots,n\}$ is constructed, where n represents the total number of nodes, and $n_2=n-n_1$ denotes the number of railway nodes. The railway subnet adjacency matrix $\boldsymbol{T}=(t_{ij})_{n_2\times n_2}$ is also constructed according to the Space-P method. If a direct ticket can be purchased between node i and node j, then $t_{ij}=1$, if not, then $t_{ij}=0$. The lowest fare and shortest travel time between two stations are recorded, and the railway subnet fare matrix $\boldsymbol{T}^{\text{fare}}=(t_{ij}^{\text{fare}})_{n_2\times n_2}$ and time matrix $\boldsymbol{T}^{\text{time}}=(t_{ij}^{\text{time}})_{n_2\times n_2}$ are constructed respectively, which are regarded as the edge weight matrix, namely the weighted adjacency matrix.

2.2 The coupling subnet

The coupling edge refers to the connecting edge that transfers passengers between stations of different transportation modes. In order to distinguish intercity transport and urban transport, a new definition of the coupling edge is given: the connecting edge that transfers passengers between intercity transport stations. The urban agglomeration contains many cities. Due to the existence of urban public transport, such as buses, subways, taxis, etc., the intercity passenger stations in the same central urban area have obvious public transport transfer relationships. Considering the impact of urban public transportation, walking and other transfer modes, the central urban area of each city is regarded as an independent traffic district. Coupling edges are added between nodes in the same traffic district, and they are coupled to each other. In this way, a number of fully coupling multi-mode passenger transport networks are constructed, which are referred to as the coupling subnets. The coupling subnet adjacency matrix $\boldsymbol{O}=(o_{ij})_{n\times n}$ is constructed. if node i and node j can be transferred by urban traffic, walking, etc., then $o_{ij}=1$, if not, then $o_{ij}=0$. The lowest transfer fare and the shortest transfer time between stations are recorded, and the coupling subnet fare matrix $\boldsymbol{O}^{\text{fare}}=(o_{ij}^{\text{fare}})_{n\times n}$ and coupling subnet time matrix $\boldsymbol{O}^{\text{time}}=(o_{ij}^{\text{time}})_{n\times n}$ are constructed respectively.

2.3 The integrated network

The highway subnet, railway subnet and coupling subnet are combined and superimposed to construct the integrated network, and the node number set of integrated network $V=\{1,2,3,\cdots,n\}$ is built, where $n=n_1+n_2$ denotes the total number of nodes. The highway subnet adjacency matrix $\boldsymbol{B}$, the railway subnet adjacency matrix $\boldsymbol{T}$, and the coupling subnet adjacency matrix $\boldsymbol{O}$ are combined to form the integrated network adjacency matrix $\boldsymbol{Z}=(z_{ij})_{n\times n}$. The fare matrix or time matrix of the highway subnet, the railway subnet, and the coupling subnet are combined to construct the integrated network edge weight matrix $\boldsymbol{W}=(w_{ij})_{n\times n}$, which is the weighted adjacency matrix. The sum of edge weights of the node is used as the node weight to construct the integrated network node weight set $H=\{h_1,h_2,h_3,\cdots,h_n\}$. Based on the above, the model of urban agglomeration integrated passenger transport network $\boldsymbol{G}=\{\boldsymbol{V},\boldsymbol{Z},\boldsymbol{W},\boldsymbol{H}\}$ is established. And the schematic diagram of urban agglomeration integrated passenger transport network is shown in Figure 1.

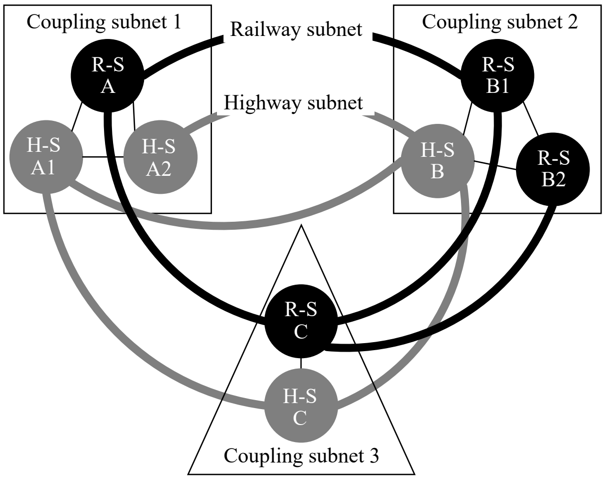

Fig. 1 Urban agglomeration integrated passenger transport network

In Figure 1, R-S and H-S are the abbreviations for railway station and highway station. And the intercity passenger stations in the same traffic district are connected in pairs through coupling edges, forming three coupling subnets. The highway subnet and the railway subnet are connected by the coupling subnets to form the urban agglomeration integrated passenger transport network.

3 Assessment of impedance accessibility

The accessibility value of a node represents the average of the shortest distance or shortest time from the node to all other nodes. The impedance efficiency of a node refers to the average of the reciprocal of the minimum impedance (shortest time or lowest fare) from the node to all other nodes. The two indexes are similar and inversely proportional. The lower the accessibility value, the better the accessibility; The higher the impedance efficiency, the better the accessibility. The efficiency is directly proportional to accessibility, so it is more intuitive to use impedance efficiency to evaluate the impedance accessibility of urban agglomeration passenger transport network. The following is the specific formula and description of the impedance efficiency.

3.1 The network efficiency

The network efficiency is a common index to measure network performance in complex network theory, which represents the average of the reciprocal of the number of edges on the shortest path between all nodes in the entire network. The network efficiency E is shown in the following equation:

$$E=\frac{1}{N(N-1)}\sum\nolimits_{i\neq j}\frac{1}{d_{ij}} \tag{1}$$

where, N represents the total number of nodes; d_{ij} denotes the number of edges on the shortest path between node i and node j.

It can be seen that the network efficiency can only measure the topological attribute and structural accessibility of the network. In order to measure the functional attribute and impedance accessibility of the network, the weighted impedance efficiency of network is constructed based on the network efficiency to evaluate the impe dance accessibility, including the impedance efficiency between nodes and the node impedance efficiency.

3.2 The node impedance efficiency

The impedance efficiency between nodes is the reciprocal of the minimum impedance (shortest time or lowest fare) between two nodes. The impedance efficiency between node i and node j is I_{ij}, as shown in the following equation:

$$I_{ij}=1/\sum\nolimits_{(i,j)\in L_{ij}}w_{ij} \tag{2}$$

where, w_{ij} represents the edge weight between node i and node j, which is calibrated by travel impedance; L_{ij} denotes the set of node pairs on the shortest path between node i and node j. For example, the shortest path between node v_1 and node v_6 is $v_1\rightarrow v_3\rightarrow v_6$, then $L_{1,6}=(1,3),(3,6)$, if there is no shortest path, then $I_{ij}=0$.

The node impedance efficiency is the average of the impedance efficiency from the node to all other nodes. The node impedance efficiency I_i is shown in the following equation:

$$I_i=\frac{1}{N-1}\sum_j I_{ij}=\frac{1}{N-1}\sum_j(1/\sum_{(i,j)\in L_{ij}}w_{ij}) \tag{3}$$

where I_{ij} represents the impedance efficiency between node i and node j.

As can be seen from Equation (3), node impedance efficiency is the average of the reciprocal of the minimum impedance (shortest time or lowest fare) from the node to all other nodes, which is used to measure the impedance accessibility of nodes in the network.

3.3 The network impedance efficiency

The network impedance efficiency is the average of node impedance efficiency. The network impedance efficiency I is shown in the following equation:

$$I = \frac{1}{N}\sum_i I_i = \frac{1}{N(N-1)}\sum_{i\neq j}\left(1/\sum_{(i,j)\in L_{ij}} w_{ij}\right) \quad (4)$$

where, N represents the total number of nodes; I_i denotes the impedance efficiency of node i; w_{ij} represents the edge weight between node i and node j; L_{ij} denotes the set of node pairs on the shortest path between node i and node j.

As can be seen from Equation (4), the network impedance efficiency is the average of the reciprocal of the minimum impedance (shortest time or lowest fare) among all nodes in the network, which is used to measure the impedance accessibility of the whole network and compare the impedance accessibility of different networks.

4 The case study

4.1 The integrated passenger transport network of Chengdu-Chongqing urban agglomeration

The scope of the Chengdu-Chongqing urban agglomeration is determined according to the State Council's Reply on the Development Plan of Chengdu-Chongqing Urban Agglomeration and the Outline for the Construction Plan of Chengdu-Chongqing Economic Circle. Since multiple long-distance bus stations in the same central urban area often have different division of labor in intercity transportation, and multiple lines often have the same departure city and arrival city, the multiple long-distance bus stations in cities at the municipal level and above are abstracted as one station and numbered, for a total of 36 highway nodes. The railway passenger stations in cities at the county level and above are selected and continued to number, for a total of 72 railway nodes. Therefore, the case study has a total of 108 nodes, and the node number set is $V = \{1,2,3,\cdots,108\}$. The tickets between the bus stations are queried point to point in the Chongqing road passenger ticketing website and the Sichuan bus passenger ticketing website, and the lowest fare is recorded to construct the highway subnet fare matrix $\boldsymbol{B}^{\text{fare}}$ and adjacency matrix $\boldsymbol{B}$. Since the specific travel time of highway passenger transport is difficult to query, the travel time of highway passenger transport is not considered for the time being. The tickets between the railway stations are checked point to point in China railway 12306 website, and the lowest fare and shortest time are recorded to construct the railway subnet fare matrix $\boldsymbol{T}^{\text{fare}}$, time matrix $\boldsymbol{T}^{\text{time}}$, adjacency matrix $\boldsymbol{T}$. Coupling edges are added between the stations with convenient transfer of urban public transportation, walking, etc., to construct the coupling subnet adjacency matrix $\boldsymbol{O}$. The adjacency matrices of highway subnet, railway subnet and coupling subnet are merged into the adjacency matrix of Chengdu-Chongqing urban agglomeration integrated passenger transport network, which is $\boldsymbol{Z} = (z_{ij})_{108\times108}$. According to the adjacency matrix of the integrated network, MATLAB is used to draw the integrated passenger transport network of Chengdu-Chongqing urban agglomeration based on Space-P, as shown in Figure 2.

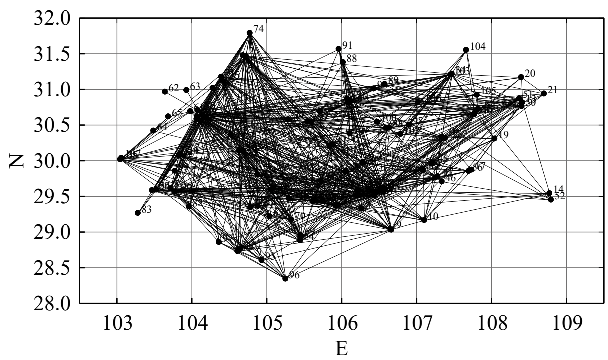

Fig. 2 Integrated passenger transport network of Chengdu-Chongqing urban agglomeration based on Space-P

In Figure 2, the nodes from 1 to 36 are highway nodes and the nodes from 37 to 108 are railway nodes. The principle of the Space-P modeling method is: if a direct single ticket can be purchased between two stations, there is an edge. There is also a related Space-L modeling method, and the principle of which is that an edge exists only between two adjacent stations on a line. There are differences between the two methods. The Space-P modeling method is used to analyze the network transfer to study the accessibility of the network, while the Space-L modeling method is used to analyze the actual route of the network, which can be used for attacking simulation such as vulnerability, robustness, etc.

4.2 Impedance accessibility of the highway subnet

In the highway passenger subnet, the impedance efficiency of each node is calculated based on the highway subnet fare matrix and node impedance efficiency index, as shown in Figure 3.

In Figure 3, the 6 highway passenger nodes with higher impedance efficiency and better accessibility are shown in Table 1.

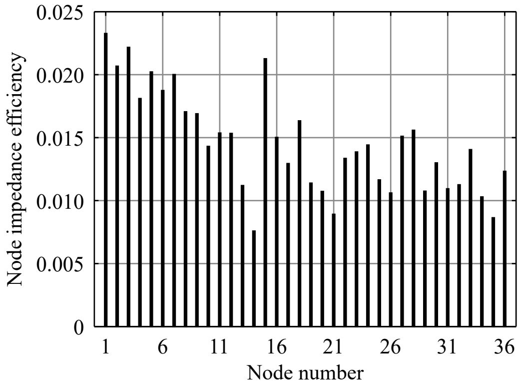

Fig. 3 Impedance efficiency of nodes in highway subnet

Table 1 Nodes in highway subnet with higher impedance efficiency

Sort (Number)	Node	Impedance efficiency
1 (1)	Chongqing	0.0233
2 (3)	Tongliang	0.0222
3 (15)	Bishan	0.0213
4 (2)	Hechuan	0.0207
5 (5)	Dazu	0.0202
6 (7)	Yongchuan	0.0200

In Table 1, the nodes with higher impedance efficiency and better accessibility are the central urban area of Chongqing and the 5 districts under its jurisdiction. These 5 districts are all within the one-hour economic circle of Chongqing and are satellite cities of Chongqing. These nodes with better accessibility are closer to each other, have better connectivity, and have smoother highway passenger transport with other cities in Sichuan Province, indicating that denser networks may have better accessibility.

In Figure 3, the 6 highway passenger nodes with lower impedance efficiency and poor accessibility are shown in Table 2.

Table 2 Nodes in highway subnet with lower impedance efficiency

Sort (Number)	Node	Impedance efficiency
36 (14)	Qianjiang	0.0076
35 (35)	Ya'an	0.0086
34 (21)	Yunyang	0.0089
33 (34)	Dazhou	0.0103
32 (26)	Mianyang	0.0106
31 (20)	Kaizhou	0.0107

The 6 nodes in Table 2 are located at the edge of the Chengdu-Chongqing urban agglomeration and are relatively isolated, so their impedance accessibility in the entire network is relatively weak, which is consistent with common sense.

4.3 Impedance accessibility of the railway subnet

In the railway passenger subnet, based on the railway subnet fare matrix and node impedance efficiency index, the cost impedance efficiency of each node is calculated, as shown in Figure 4.

In Figure 4, there are 7 railway passenger nodes with higher cost impedance efficiency and good accessibility, as shown in Table 3.

It can be seen from Figure 4 and Table 3 that the railway stations in the central urban areas of Chengdu and

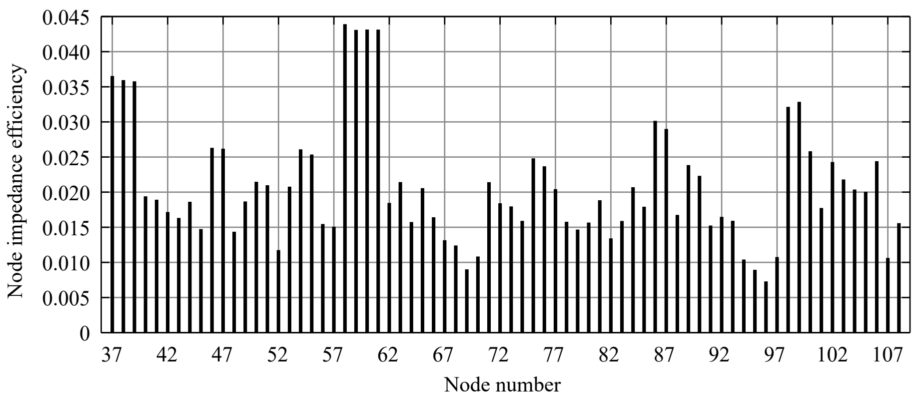

Fig. 4 Cost impedance efficiency of nodes in railway subnet

Table 3 Nodes in railway subnet with higher cost impedance efficiency

Sort (Number)	Node (Railway Station)	Impedance efficiency
1 (58)	Chengdu	0.04382
2 (60)	Chengdu South	0.04305
3 (61)	Chengdu West	0.04304
4 (59)	Chengdu East	0.04300
5 (37)	Chongqing North	0.03644
6 (38)	Chongqing West	0.03585
7 (39)	Shapingba	0.03568

Chongqing have higher node impedance efficiency and better accessibility in terms of travel costs. Due to the convenience of transfer in the city, multiple stations in the same city are closely connected, which will make the impedance efficiency of these stations higher. For example, these stations in Chengdu and Chongqing, as well as Fuling Railway Station and Fuling North Railway Station (No. 46, 47), Nanchong Railway Station and Nanchong North Railway Station (No. 86, 87), which have higher impedance efficiency and better accessibility due to the convenient transfer and close connection.

Based on the railway subnet time matrix and node impedance efficiency index, the time impedance efficiency of each node is calculated, as shown in Figure 5.

The trend in Figure 5 is similar to that in Figure 4, the railway stations in the central urban areas of Chongqing and Chengdu have higher impedance efficiency and better accessibility in terms of travel time. In Figure 5, some single nodes without intra-city transfers perform well in terms of time impedance efficiency, such as Dazu South Railway Station (No. 42), Rongchang North Railway Station (No. 43), Yongchuan East Railway Station (No. 44), Neijiang North Station (No. No. 78), etc. Because these stations are the intermediate stations of the Chengdu-Chongqing High-Speed Railway, which operates at a speed of 300 km/h (some CR400 trains run at 350 km/h), the transport speed is faster and the time consumption is less, so the time impedance efficiency of these nodes is higher. The reason for the lower cost impedance efficiency of these nodes is that the cost of high-speed EMUs is slightly higher than that of ordinary EMUs, intercity EMUs, and fast passenger trains.

4.4 Impedance accessibility of the integrated network

The fare matrices of the highway subnet, railway subnet, and coupling subnet are combined into the edge weight matrix of the integrated network, and the impedance efficiency of each node of the integrated network is calculated, as shown in Figure 6.

According to Figure 6, the stations in the central urban area of Chongqing (No. 1, 37, 38, 39) and the stations in the central urban area of Chengdu (No. 22, 58, 59, 60, 61) still show strong accessibility in the integrated passenger transport network of urban agglomeration. Not only that, Fuling Bus Station, Fuling Railway Station, Fuling North Railway Station (No. 11, 46, 47), Nanchong Bus Station, Nanchong Railway Station, Nanchong North Railway Station (No. 30, 86, 87) also show strong accessibility, mainly due to the coupling association of multiple stations.

The network impedance efficiency of the highway subnet, railway subnet and integrated network is calculated, as shown in Figure 7.

In Figure 7, the impedance efficiency of the highway subnet is 0.0145, and the impedance efficiency of the

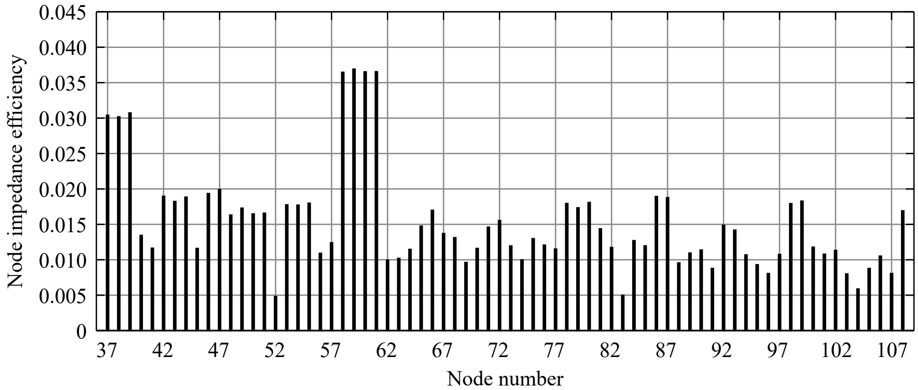

Fig. 5 Time impedance efficiency of nodes in railway subnet

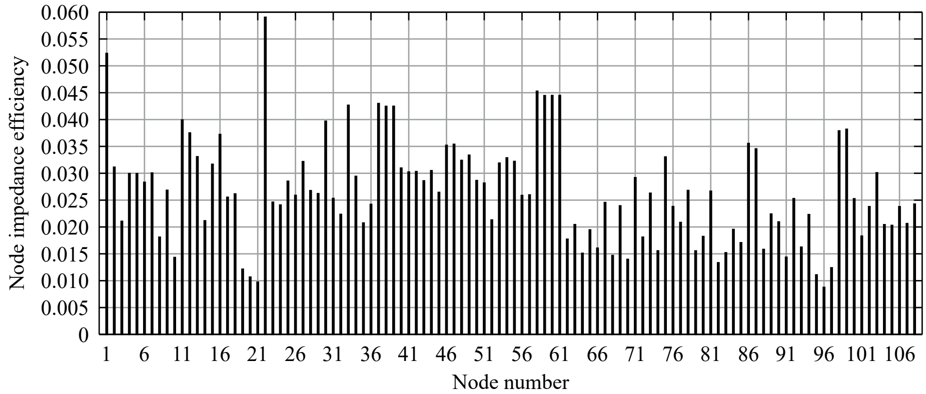

Fig. 6 Impedance efficiency of nodes in integrated network

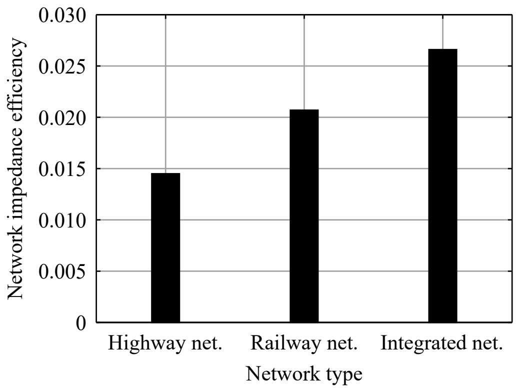

Fig. 7 Impedance efficiency comparison of networks

railway subnet is 0.0207. The impedance efficiency of the integrated network after the combination of the highway subnet and the railway subnet is 0.0266, which is 83.4% higher than that of the highway subnet and 28.5% higher than that of the railway subnet. It can be seen that the coupling of the highway subnet and the railway subnet improves the impedance accessibility of the urban agglomeration passenger transport network, and further reduces the travel impedance of passengers.

5 Conclusions

This paper proposes a modeling method of urban agglomeration integrated passenger transport network considering intra-city traffic transfer when studying intercity transport within the same urban agglomeration, which is closer to the actual situation. And this paper studies the impedance accessibility of urban agglomeration passenger transport network from the perspective of travel cost and time. The integrated passenger transport network in Chengdu-Chongqing urban agglomeration is taken as a case study to identify the stations with lower travel cost, that is, higher node impedance efficiency and better impedance accessibility, and to evaluate and compare the impedance accessibility of the networks. The conclusions and prospects are as follows:

(1) The case study shows that the impedance efficiency of multiple coupling nodes in Chengdu, Chongqing, Nanchong and some other cities is relatively high, mainly due to the convenience of intra-city transfer, which makes the coupling nodes show better impedance accessibility. Therefore, urban transport transfer is a link that can not be ignored in the study of urban agglomeration integrated passenger transport network.

(2) The impedance efficiency of the integrated network is higher than that of the highway subnet and the railway subnet, which indicates that the coupling of multiple transport modes can improve the impedance accessibility of urban agglomeration passenger transport network and further reduce the travel cost of passengers. Therefore, it is necessary to vigorously promote the coupling and connection between different transport modes, build a more coordinated integrated passenger transport network, and further reduce the travel impedance.

(3) The cost impedance and the time impedance are two different attributes for analyzing network accessibility. Some nodes have better time accessibility but poor cost accessibility, and some nodes have better cost accessibility but poor time accessibility. In further research, we can try to construct the impedance function to combine the two attributes organically and evaluate the network impedance accessibility by taking into account the two attributes.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Acknowledgments

The work presented in this paper was partially funded by the National Natural Science Foundation of China (No.62063023); Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region (NJYT22099).

References

[1] Candelieri, A.; Galuzzi, B. G.; Giordani, I.; et al. Vulnerability of public transportation networks against directed attacks and cascading failures[J]. Public Transport, 2019, 11(1): 27-49.

[2] Wang, G. J.; Lv, W. H.; Gao, G.; et al. Study on detour scheme for failure of transit station based on complex network[J]. Journal of Highway and Transportation Research and Development, 2020, 37(11): 107-117.

[3] Lu, Q. C.; Cui, X.; Xu, B.; et al. Vulnerability research of rail transit network under bus connection scenarios[J]. China Safety Science Journal, 2021, 31(8): 141-146.

[4] Feng, X.; Jia, H. C. Aviation network robustness considering node failure and edge failure[J]. Journal of Beijing Jiaotong University, 2021, 45(5): 84–92.

[5] Wei, Z. L.; Gan, Y. J.; Zhao, P. Characteristic research of urban complex traffic network[J]. Journal of Transportation Systems Engineering and Information Technology, 2015, 15(1): 106-111.

[6] Ji, X. F.; Wu, J. S. A method for extracting characteristics of highway passenger transport network spatial structure in urban agglomeration[J]. Journal of Highway and Transportation Research and Development, 2017, 34(10): 128-134.

[7] Li, C. B.; Wei, L.; Hao, Y. C. Research on characteristics of city agglomeration compound traffic network[J]. Journal of System Simulation, 2016, 28(12): 2958-2965.

[8] Mao, J. N.; LIU, L. A method for identifying node importance of passenger transport network in urban agglomeration[J]. Journal of Highway and Transportation Research and Development, 2019, 36(5): 130-137.

[9] Li, C. B.; Zhang, S.; Yang, Z. C.; et al. Invulnerability simulation in urban agglomeration passenger traffic network under targeted attacks[J]. Journal of Transportation Systems Engineering and Information Technology, 2019, 19(2): 14-21.

[10] Zhang, L.; Zhang, X. B.; Yuan, S. G.; et al. Economic, social, and ecological impact evaluation of traffic network in Beijing–Tianjin–Hebei urban agglomeration based on the entropy weight TOPSIS method[J]. Sustainability, 2021, 13(4): 1862.

[11] Guo, K. X.; Peng, G. Q.; Zhen, X. Q.; et al. Analysis and evaluation of comprehensive transportation network integration in beibu gulf urban agglomeration[J]. Geography and Geo-information Science, 2021, 37(4): 57-63.

[12] Xiao, H. W.; Wang, Q. X.; Zhang, J. Analysis of the characteristics and influencing factors of the inter-locked network of chengdu-chongqing urban agglomeration: A perspective of highway passenger transport[J]. Shanghai Urban Planning Review, 2021(2): 128-135.

[13] Guan, W.; Wu, J. J.; Gao, Z. Y. Transportation network systems engineering[J]. Journal of Transportation Systems Engineering and Information Technology, 2020, 20(6): 9-21.

[14] Koenig, J. G. Indicators of urban accessibility: Theory and Application[J]. Transportation, 1980, 9(2): 145–172.

[15] Aklilu, A.; Necha, T. Analysis of the spatial accessibility of addis ababa's light rail transit: the case of east–west corridor[J]. Urban Rail Transit, 2018, 4(1): 35–48.

[16] Wang, Z. B.; Xu, J. G.; Fang, C. L.; et al. The study on county accessibility in china: characteristics and effects on population agglomeration[J]. Journal of Geographical Sciences, 2011, 21(1): 18-34.

[17] Zong, H. M.; Huang, Y. The impact of high-speed rail on regional accessibility and regional spatial interactions: A case study of chengdu-chongqing urban agglomeration[J]. Human Geography, 2019, 34(3): 99-107,127.

[18] Xu, M. F.; Ou, X. P.; Wang, Y. Q. Study on highway accessibility of urban agglomerations and its connection improvement[J]. China Journal of Highway and Transport, 2020, 33(11): 245-254.

[19] Hong, D. F.; Luo, H. S.; Qin, J. Research on the coupling development of transportation network accessibility and urbanization in border areas of yunnan province[J]. Hubei Agricultural Sciences, 2021, 60(7): 191-196.

[20] Kong, F. Y.; Zhou, Y. F.; Li, X. Z. Characteristic analysis of urban public transport networks based on space-p complex network model[J]. Computer Science, 2018, 45(8): 125-130.