

Passenger flow dynamic assignment model of urban mass transit and its application during interval interrupted operation

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Abstract: In order to find a method which can describe the passenger flow dynamical distribution of urban mass transit during interval interrupted operation, an urban railway network topology model was built based on the travel path dual graph by considering interchange, crowd and congestion. The breadth first valid travel path search algorithm is proposed, and the multipath passenger flow distribution logit model is improved. According to the characteristics of passengers under the interruption condition, the distribution rules of different types of passenger flow are proposed. The method of calculating the aggregation number of station is proposed for the case of insufficient transport capacity. Finally, the passenger flow of Beijing urban mass transit is simulated for the case study. The results show that the relative error of most of transfer passenger flow is below 10%. The proposed model and algorithm can accurately assign the daily passenger flow, which provides a theoretical basis for urban mass transit emergency management and decision.

Key words: urban mass transit; dynamic; disequilibrium distribution; local disruption

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The urban mass transit system is a type of green public transportation, which has the advantage of low energy consumption, low pollution and high comfort level. The system can realize efficient transport for a large number of passengers. Local disruption leads to a wide range of delay and the passenger retention phenomenon in peak hours. It affects the network efficiency and reliability of the urban public transport system significantly. Therefore, an important question is how to quantize the daily traffic distribution under fault conditions and develop a reasonable plan for passenger transport organization.

Most models of passenger flow assignment of urban

mass transit networks are based on the distribution theory of urban roads. The traffic distribution method was first proposed using Wardrop concepts and definitions of the road network equilibrium^[1]. More recently, the network traffic assignment was divided into two types: equilibrium and disequilibrium.

For equilibrium distribution, Tian et al.^[2] proposed the dynamic equilibrium flow and dynamic stochastic assignment models. Poon et al.^[3] proposed the dynamic traffic flow distribution model and solved the distribution of the network and wiring problem using simulations.

For disequilibrium distribution, Daganzo et al.^[4] proposed the multipath probabilistic distribution model. Since the number of calculations needed is large, the model is not suitable for large-scale networks. Dial^[5] proposed the logit model of road traffic networks. Vuk et al.^[6] proposed a mathematical optimization logit model.

Schmöcker et al.^[7] realized dynamic assignment based on frequency. The cost of boarding failure probability is introduced. Kato et al.^[8] analyzed six traffic distribution models by using travel route choice data on Tokyo, Japan. It is concluded that the stochastic traffic assignment based on the probit model leads to minimal deviation based on actual situation. Emmanuel et al.^[9] built a microscopic model framework based on multi-agent simulation technics of city traffic. Grube et al.^[10] built a simulation model of the rail transit system based on the event-driven method. The advantage is adding passenger flow as factors in the simulation process. The disadvantage of the model is that the train operation process is relatively simple. Schmöcker et al.^[11] considered the frequency of passenger seat in travel cost based on the departure frequency. Nuzzolo et al.^[12] constructed a dynamic passenger assignment model. It contained a transportation service network of operation plan. Compared to other models, their model considers strict constraints of transportation capacity. When describing a passenger route choice, the model considers the departure time, stops, trains and other factors. Shi et al.^[13] proposed a multi-level passenger equilibrium model based on train transfer reliability.

Some of the above methods do not well reflect the urban rail transportation characteristics. The path impedance is not identified by the traveler choice under the conges-

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tion. In this article, a passenger flow disequilibrium assignment method for urban mass transit networks is analyzed. An urban railway network topology model is built based on the travel path dual graph by considering interchange, crowd and congestion. The model of multipath stochastic assignment and the calculation method of retention are proposed in the case of insufficient transport capacity. We propose a model which can effectively describe the passenger flow dynamical distribution of urban mass transit during interval interrupted operation.

1 Methodology

Traffic flow assignment methods are used to predict the OD traffic volume. According to network conditions, we assign the volume to every path in the network. Then, we can obtain the traffic flow of the road network in each section and the cost of the OD matrix.

In actual mass transit systems, the network structure is complex. There is a great deal of randomness in route choices. Travelers do not always choose the shortest path, and they select reasonable alternative paths randomly. Random assignment is more suitable for mass transit networks. A dynamic stochastic traffic assignment model is proposed based on the characteristics of mass transit road networks, expected utility theory and logit model.

1.1 Network impedance model based on dual graph of travel routes

1.1.1 Dual graph of urban mass transit travel routes

The existing research on urban mass transit passenger flow distribution is mostly based on the original figures of mass transit network. In the urban road traffic network topology structure chart, the network nodes represent two or more intersections, and the lines are roads. In urban mass transit network topology, nodes represent stations, and lines show the driving range of stations.

In Fig. 1, a traveler goes from station R of line 3 to station S of line 4. The travel path chosen by travellers is R—A—3a—B—1c—E—1d—F—4b—H—S. The travel path can be represented in Fig. 2.

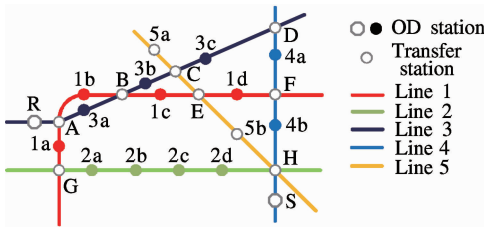


Fig. 1 Original virtual figure of urban mass transit network topology

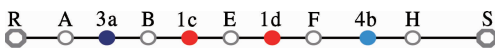


Fig. 2 Urban mass transit travel path sketch diagram

In order to study the traveler route choice behavior more reasonably, we construct the dual graph, as shown in Fig. 3.

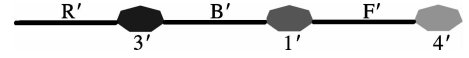


Fig. 3 Urban mass transit route dual graph

Station R in Fig. 2 abstracts to section R'. The transfer stations of B and F in Fig. 2 abstract to sections of B' and F', respectively. At the non-transfer station, there is no boarding or alighting. The segments and stations between stations R and B of line 3 in Fig. 1 correspond to node 3' in Fig. 3. The segments and stations between B and F of line 1 in Fig. 1 correspond to node 1' in Fig. 3. The segments and stations between F and S of line 4 in Fig. 1 correspond to node 4' in Fig. 3. The destination station S is incorporated to node 4'. We abstract stations to sections, sections and stations to nodes. This is a dual graph. It calculates the impedance factors and structure properties of urban mass transit networks according to the road traffic.

1.1.2 Impedance model of the urban mass transit network based on travel path dual graph

The dual graph of the mass transit road network consists of sections and nodes. The impedance of the travel path consists of node impedance and road impedance. The two have different affecting factors.

In the dual graph of the urban mass transit network, a segment expresses a site of the original figure. Each feasible path of the OD contains a starting section and more transfer sections. The starting section corresponds to station O of the traveler's OD pair. The transfer segments correspond to the transfer stations on the passenger's way. The impedance of the transfer segment k can be represented as

$$\bar{T}_k^{\text{tr}} = \bar{T}_k^{\text{wait}} + \gamma \bar{T}_k^{\text{walk}} \quad (1)$$

where \bar{T}_k^{wait} is the average waiting time of retention; \bar{T}_k^{walk} is the transfer walking time; γ is a parameter, and its value is 3. It represents the impedance of the combination process of walking and waiting time.

In the dual graph of urban mass transit network, nodes indicate that the traveler paths go from boarding to alighting.

In daily operation conditions, a train stops at each station on the way. Its running time consists of traveling time $T_{i,i+1}^{\text{run}}$ and dwelling time T_{i+1}^{stop} . Therefore, the impedance of node n can be expressed as

$$T_n^{\text{node}} = \sum_k T_{i,i+1}^{\text{run}} + \sum_{k=1} T_{i+1}^{\text{stop}} \quad (2)$$

Eq. (2) shows the number of stations in the process of traveler going from boarding to alighting. The start of running time is the start of train, and the end time is the train stop.

It is proposed that the calculation function caused by

overcrowding makes the traveler's subjective perception of the travel time longer. The calculation function used in this paper is

$$Y(x_{\max}) = \begin{cases} \frac{x_{\max} - fn}{fn} \delta & x_{\max} > fn \\ 0 & x_{\max} \leq fn \end{cases} \quad (3)$$

where x_{\max} is the node of the dual graph in the original figure corresponding to the maximum passenger flow; f is the departure frequency; n is the rated number of train passengers; and δ is a parameter.

In conclusion, the generalized time impedance of node n is

$$\bar{T}_n^{\text{node}} = (1 + Y(x_{\max})) T_n^{\text{node}} \quad (4)$$

Therefore, any path r of w comprehensive impedance can be defined as

$$T_r^w = \sum_i \bar{T}_i^{\text{node}} + \lambda \left(\sum_j \bar{T}_j^{\text{tr}} + \bar{T}_o^{\text{wait}} \right) \quad \forall w, r \quad (5)$$

where λ is the dimensional transformation parameter between the node and section, which is usually greater than 1. We set λ to be 1.6. \bar{T}_o^{wait} is the impedance of station O.

1.2 Effective path search algorithm based on breadth first

In urban mass transit systems, a passengers' traveling path consists of multiple segments.

Let c_{rs} be the travel cost of path p_{rs} . It contains the time of the train running, transfer, going into and out of the station, crowding and retention.

Let $V^{(k)}$ be the transfer nodes of layer k of the search, and V^T be a possible key nodes collection for searching the identified next layer. The effective path search algorithm is shown in Algorithm 1.

Algorithm 1 Valid path search

$i = 0, k = 0, j = 1$

While search $V_{i,j}^{(k)}$

Calculate $c(V_0^0, V_{i,j}^{(k)})$

if it is a value path

Record $P(V_{i,j}^{(k)})$

if $V_{i,j}^{(k)} = S$

Record $V_{i,j}^{(k)}$

if k layer nodes are searching over

$V^{(K)} \leftarrow V^T$

if $V^{(K)} = \emptyset$

$k = k + 1, j = 1$

end if

end if

else if $V_{i,j}^{(k)} = T$

Record path $V_{i,j}^{(k)}$

end if

Return

where V_0^0 is the start of a valid path; $V_i^{(k)}$ is the node of layer k ; $V_{i,j}^{(k)}$ is the node of the same search direction as

$V_i^{(k)}$; $c(V_0^0, V_{i,j}^{(k)})$ is the cost; S is the transfer station; T is the terminal station; path is the path between two points; $P(\cdot)$ is the property of node; i, j, k are the loop variables. The value path condition is the Floyd shortest path algorithm.

In order to narrow the search scope of effective path, we add the determination condition of effective path, which can improve the algorithm efficiency and make the algorithm suitable for large-scale networks.

1.3 Stochastic dynamic assignment model of passenger flows based on modified logit

The traditional logit model is based on the absolute deviation of the traveler perception path as a measure of the probability of traveler route choice. In actual application, an overlap path is assigned too much flow. The result of passenger flow assignment is also concentrated. When the impedance is large, the calculation error is large.

Therefore, the traditional logit model should be improved. The relative impedance is used instead of the logit route choice model. It can be expressed as

$$p_i^w = \frac{\exp\left(-\theta \frac{T_i^w}{\bar{T}^w}\right)}{\sum_{j \in R_w} \exp\left(-\theta \frac{T_j^w}{\bar{T}^w}\right)} \quad \forall i \quad (6)$$

where \bar{T}^w is the average impedance of all OD paths. The value of θ is 19.6.

The distribution method is based on paths. We use the passenger flow data of the urban mass transit AFC system with a time interval of 5 min. Based on the traveler route choice model of the dual graph, the impedance of the path varies with the change of travelers waiting time and compartments crowding degree. The travelers waiting time at a station is determined by the passenger flow statistics of boarding and segment passenger flows. The compartments crowded degree is calculated by the segment passenger flows. Since different periods are present in the statistics, the passenger flows of boarding and intervals of section passenger flows are different. Therefore, the distribution of the passenger flow of the urban rail transportation network belongs to the dynamic distributions of passenger flows. The passenger flow assignment algorithm process of the improved logit model is shown in Fig. 4.

1.4 Application of passenger flow assignment model on a local disruption

1.4.1 Calculation method of retention in the case of insufficient transport capacity

When the rail transportation capacity is insufficient to meet the demand of people, the traveler retention phenomenon appears, which causes a longer travel time.

At time t_0 , the effective capacity of the train is at its

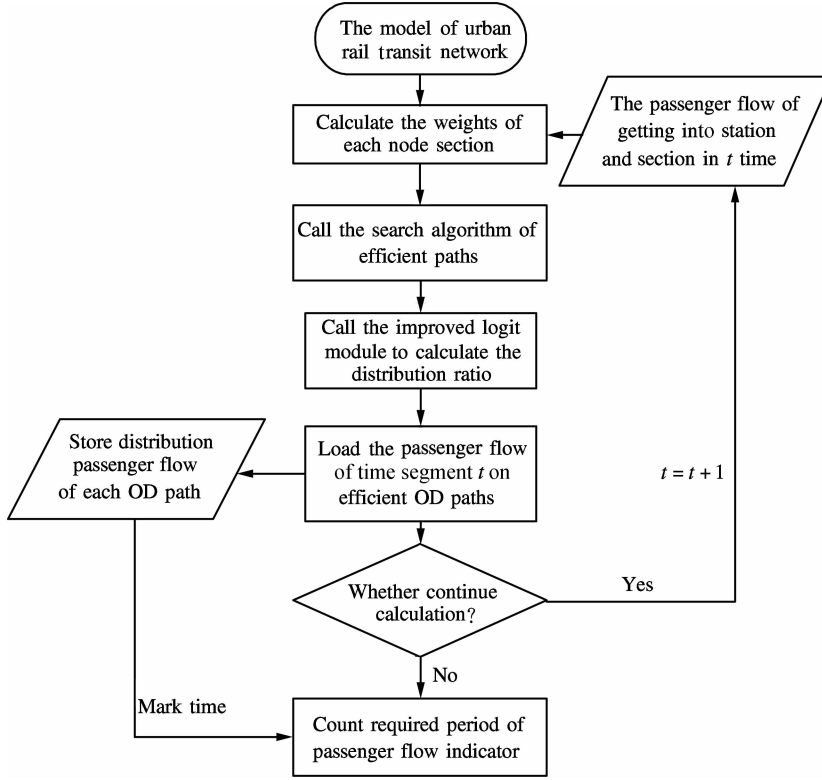


Fig. 4 Passenger flow assignment algorithm process of improved logit model

saturation level, and the retention phenomenon occurs. At time t_1 , the next train arrives. At time t_2 , the next train goes away from the station, so the expression of retention in period $t_0 - t_2$ can be expressed as

$$\text{num}(t) = \int_{t_0}^{t_1} f(t) dt - \int_{t_1}^{t_2} g(t) dt \quad (7)$$

The analytic expression does not consider passenger boarding. On the one hand, since in the morning and evening peak hours there is the tidal flow phenomenon of retention, the number of passengers getting into stations is larger. On the other hand, when the train is at the station, the equivalent exchange of compartment passenger numbers does not lead to a change in the number of passengers at the station. So, it is reasonable to consider people getting out of the station.

At time t , the retention people $\text{num}(t)$ in line l of any station i can be seen as

$$\begin{aligned} \text{num}_i(t) = & \text{num}_i(t-1) + O_i(t) - (x_c(t) + D_i(t)) + \\ & \left(\sum_k (x_i^{m,l} - x_i^{l,m}) \right) \partial = \text{num}_i(t-1) + O_i(t) - \\ & D_i(t) - fc + x_{ji}(t) + \left(\sum_{k=1} (x_i^{m,l} - x_i^{l,m}) \right) \partial \end{aligned} \quad (8)$$

where $O_i(t)$ is the number of passengers getting into station i during period t ; $D_i(t)$ is the number of passengers getting out of station i during period t ; f is the departure frequency, and its value is the reciprocal of the departure interval; c is the rated capacity of the train; $x_{ji}(t)$ is the section passenger flow of station i at time t for period j -

i ; ∂ is a variable such that if station i is a transfer station, its value is 1, otherwise it is 0; k is the connect line direction of station i ; $x_i^{m,l}$ is the transfer passenger flow of the exchange line m to l ; $x_i^{l,m}$ is the swap-out passenger flow of the exchange line l to m .

1.4.2 Analysis and calculation of passenger flow impact during interval interrupted operation

As the train traffic organization scheme changes, the network topology changes. Some effective paths of the OD pairs during the interruption are disturbed. Travelers focus on effective paths, and find alternative paths avoiding interruption intervals. Every alternative path's impedance value does not change due to interruption. However, its probability distribution needs to be calculated again.

We suppose that in the network G during period $T_1 - T_2$, section (a, b) is interrupted. We classify all the passenger areas as follows:

Type 1 Before T_1 , avoiding the interruption interval (a, b) passenger flow;

Type 2 The passenger flow has not yet arrived at the interruption interval (a, b) in period $T_1 - T_2$;

Type 3 The passenger flow, which enters the traffic interruption interval (a, b) before T_1 , goes through the interruption interval (a, b) in period $T_1 - T_2$;

Type 4 Before T_1 into the network, the passenger flow is through the interruption interval (a, b) in period $T_1 - T_2$;

Type 5 In period $T_1 - T_2$, the effective path of the OD

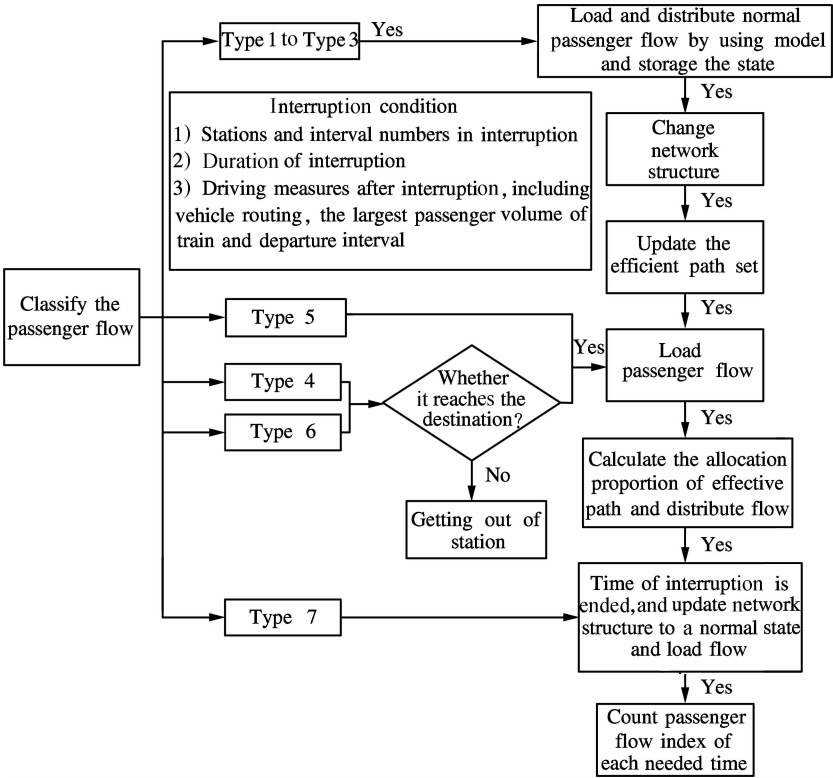


Fig. 5 Passenger flow assignment procedure under interruption conditions

does not contain the interruption interval;

Type 6 In period $T_1 - T_2$, the effective path of the OD contains the interruption interval;

Type 7 The passenger flow after the moment T_2 .

The assignment process is shown in Fig. 5.

2 Example Analysis

The Beijing mass transit network is chosen as the research object, using the passenger flow OD data of the AFC system as the input data, in order to validate the method of the disequilibrium dynamic distribution. The

case uses the passenger data of March 4, 2014. It is the Beijing urban rail transit morning peak passenger flow data. It contains 16 lines, 274 stations (repeating transfer stations). We have built the database by numbering every line and station of the Beijing urban railway network. Line 1 of the Beijing urban mass transit is named 01 in the database. Line 1 contains 23 stations. We number each station. Pingguoyuan station of line 1 is numbered 103, Gucheng station of line 1 is numbered 104 and so on. The information is presented in Tab. 1.

Tab. 1 Information on Beijing urban railway network

Line	Number of line	Number of station	Number of transfers
1	01	103-125	110, 111, 114, 115, 119, 120, 122, 124, 125
2	02	201-218	201, 202, 204, 206, 209, 211, 212, 214, 215, 217
4	04	421-467	425, 427, 433, 439, 443, 447, 453, 455, 457, 461, 465
5	05	521-565	527, 533, 537, 543, 549, 553, 555, 557, 561, 565
6	06	621-661	623, 627, 633, 635, 641, 643, 647
8	08	805-839	805, 813, 825, 829, 835, 839
9	09	921-945	921, 923, 927, 933, 945
10	10	1001-1091	1005, 1009, 1017, 1021, 1023, 1027, 1035, 1039, 1043, 1053, 1061, 1075, 1081, 1085
13	13	1321-1351	1321, 1325, 1331, 1337, 1339, 1343, 1345, 1351
14	14	1421-1433	1431, 1433
15	15	1539-1563	1539, 1541
Changping	94	9319-9341	
Fangshan	95	9429-9441	9441
Yizhuang	96	9521-9541	9521
Batong	97	9621-9645	9621
Daxing	93	9701-9713	9701, 9702

2.1 Effectiveness of the passenger flow assignment and accuracy verification

We can calculate the impedance of valid travel path and assignment probability based on train and passenger flow information of the Beijing rail transit. We select three OD

pairs randomly. On the basis of passenger flow investigation and many times experiment, we determine the parameters of modes are as follows. We set γ to be 3 in Eq. (1), λ is 1.6 in Eq. (5), and θ is 19.6 in Eq. (6). The valid path impedance and assignment probabilities are shown in Tab. 2.

Tab. 2 Multipath assignment proportion during different periods of time of some OD pairs

OD	Time	Number	Way to the stations	Impedance	Choice
467-204	7:00	1	467-465-463-461-459-457-455-206-205-204	27.690	0.530
		2	467-447-451-115-114-204	30.700	0.370
		3	467-447-635-633-202-203-204	41.637	0.100
	7:30	1	467-465-463-461-459-457-455-206-205-204	27.659	0.527
		2	467-447-451-115-114-204	30.710	0.366
		3	467-447-635-633-202-203-204	41.098	0.106
	8:00	1	467-465-463-461-459-457-455-206-205-204	28.269	0.506
		2	467-447-451-115-114-204	30.768	0.378
		3	467-447-635-633-202-203-204	40.927	0.116
	8:30	1	467-465-463-461-459-457-455-206-205-204	27.619	0.527
		2	467-447-451-115-114-204	30.701	0.364
		3	467-447-635-633-202-203-204	40.801	0.109
104-549	7:00	1	104-119-553-551-549	47.206	0.485
		2	104-114-204-203-202-633-635-637-639-641-549	55.508	0.271
		3	104-114-204-201-218-217-216-215-543-549	57.007	0.244
	7:30	1	104-119-553-551-549	66.628	0.433
		2	104-114-204-203-202-633-635-637-639-641-549	74.307	0.296
		3	104-114-204-201-218-217-216-215-543-549	76.161	0.270
	8:00	1	104-119-553-551-549	119.618	0.418
		2	104-114-204-203-202-633-635-637-639-641-549	122.729	0.384
		3	104-114-204-201-218-217-216-215-543-549	146.612	0.198
	8:30	1	104-119-553-551-549	53.904	0.461
		2	104-114-204-203-202-633-635-637-639-641-549	61.933	0.282
		3	104-114-204-203-202-201-218-217-216-215-543-549	63.414	0.257
103-209	7:00	1	103-114-204-205-206-207-208-209	45.017	0.450
		2	103-119-553-555-209	53.317	0.245
		3	103-120-211-210-209	50.317	0.305
	7:30	1	103-114-204-205-206-207-208-209	64.013	0.422
		2	103-119-553-555-209	72.618	0.271
		3	103-120-211-210-209	70.155	0.307
	8:00	1	103-114-204-205-206-207-208-209	117.432	0.383
		2	103-119-553-555-209	125.726	0.303
		3	103-120-211-210-209	124.472	0.314
	8:30	1	103-114-204-205-206-207-208-209	46.727	0.447
		2	103-119-553-555-209	55.057	0.248
		3	103-120-211-210-209	52.112	0.305

Using the passenger flow data of Beijing mass transit train system, we can calculate the effective path, impedance and probability distribution of all OD pairs of the network at different times. Therefore, this article chooses 20 interchange directions. The output cumulative transfer flows of 20 directions are compared to the real ones during early peak hours 8:05-8:50 on March 4, 2014. The results are shown in Fig. 6.

From Fig. 7, we can see that the results are consistent with the actual ones. In addition to 115-453, 212-643, 643-212 (station numbers), the three directions' relative error values are around 15%. The other directions are

controlled within 10%. This also proves that the urban mass transit passenger flow disequilibrium dynamic allocation model and algorithm are accurate.

2.2 Analysis of passenger flow impact during interruption

In order to analyze the influence of interruptions, this article assumes the following interruption events: From Fuxingmen to Dongdan of line 1, the interruption of two-way directions during the morning peak hours 8:05 to 8:50 and the duration of the interruption is 45 min. We consider the following interruption events occurring at

8:05; Pingguoyuan-Fuxingmen and Dongdan-Sihuidong. At the same time, during the interruption interval, the stations are sealed. We make the comparative analysis of different direction interchange passenger flows at each transfer station and section, station retention changes of line 1, and interruption influence range of dynamic change.

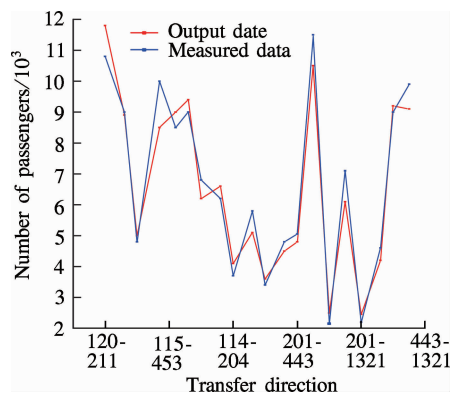


Fig. 6 Comparative analysis of the algorithm calculation results

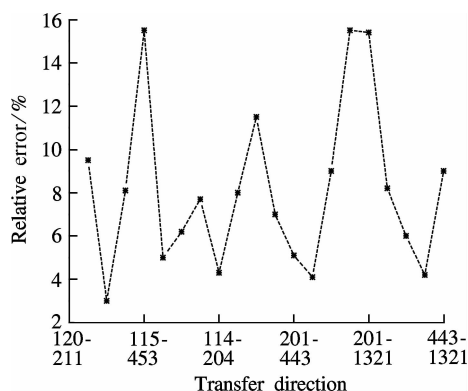


Fig. 7 Relative error analysis

1) Comparative analysis of the transfer passenger flows under normal and interruption conditions.

From Fig. 8, at the interchange station Fuxingmen of line 1 and line 2 under normal and interrupt conditions, the transfer amount has a clear change after the interruption occurs. During the interruption period, the transfer flow is larger than normal. Until the interruption is over, the value goes back to normal.

2) The retention number changing at relevant stations during interruption

Regarding retention at Xidan, Tiananmenxi, Tiananmendong, and Wangfujing stations, the passenger flows getting into the stations lose accessibility. The algorithm takes measures to seal the stations, and the retention of the stations is not taken into consideration. Since Fuxingmen and Dongdan stations are the start of a small cross road, they are interchange stations. The retention and dissipation characteristics of the stations are more apparent. From Fig. 9, we can see that the retention numbers of

Dongdan station begin to increase after the interruption. Since the capacity of line decreases, its aggregation numbers continue to increase, with the peak appearing at 9:05. After the system goes back to normal operation, the line has greater capacity, which is consistent with the retention characteristics in actual situation.

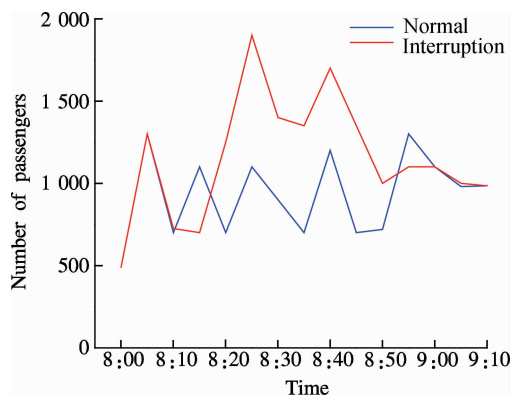


Fig. 8 Numbers from line 1 to line 2 at Fuxingmen station under normal and interruption conditions

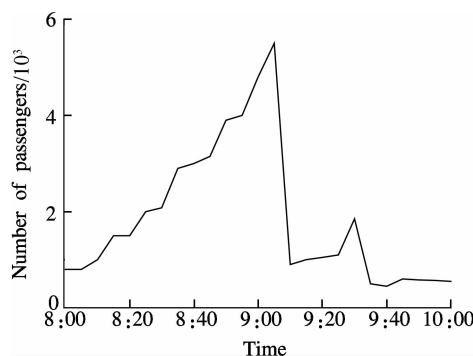


Fig. 9 Aggregation number variations in Dongdan station during the interruption

3 Conclusion

By analyzing the disequilibrium characteristics of urban mass transit network, the dual graph of the topology model of the urban mass transit network and the breadth first algorithm of effective path search are proposed. The algorithm for large-scale networks can provide more effective path search, and meet operational efficiency needs of the passenger flow dynamic distribution. A disequilibrium stochastic dynamic model is established by the improved logit model. A calculation method of the aggregating number is proposed according to the passenger flow characteristics of interruption in the case of insufficient transport capacity. The real network structure and data on Beijing mass transit system are used. The results show that the passenger flow distribution method can realize disequilibrium stochastic dynamic allocation under normal conditions and during interruption, reasonably reflecting changes in passenger flows and verifying the effectiveness of the algorithm.

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中断条件下的城市轨道交通客流量动态分配模型及其应用

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摘要:为了较为准确地对城市轨道交通在运营中断等特殊条件下的客流量动态分配及其影响进行分析计算,在综合考虑换乘、拥挤、等待等因素基础上构建了基于出行路径对偶图的阻抗模型.采用了基于广度优先的有效路径搜索算法,构建了改进的 Logit 模型.根据中断条件下乘客的出行特点,给出了不同类别客流的分配规则,并提出了中断运力不足情况下站内聚集人数计算方法.最后,以北京城市轨道交通某日客流量为例进行实验.结果表明,大部分换乘方向的相对误差值在 10% 左右.该模型与算法能够较为准确地对日常客流量进行分配,为城市轨道交通应急管理及决策支持提供了理论依据.

关键词:城市轨道交通;动态;非均衡分配;局部中断

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