Design of Evacuation Plan for Shenyang Metro Line 9 Based on Game Passenger Flow Distribution

Weidong Liu, Quanbo Fu, Wenqi Sun, and Rongze Yu

Abstract In view of the increasingly complex road network structure and the long evacuation time of the subway, this paper studies the design of the multi-path evacuation passenger flow distribution ratio based on the game theory model and the matrix game method. The evacuation plan was designed in combination with the transfer station of the Olympic Sports Center of Shenyang Metro Line 9, and the plan was optimized from the three perspectives of facilities, passenger flow and station halls. Use Anylogic simulation software to construct the Olympic Sports Center subway station and simulate the evacuation plan. The simulation results show that the evacuation efficiency of personnel has been significantly improved after optimization; emergency treatment measures effectively guide personnel to escape from multiple evacuation exits, reducing the problem of personnel retention and improving the utilization efficiency of evacuation exits; the game path allocation method is used to clarify the number of personnel allocated in the complex subway network, and improve the utilization rate of roads and the efficiency of evacuation.

Keywords Subway · Evacuation · Game theory

1 Introduction

As the main force of urban passenger transportation, the subway needs to complete a large amount of passenger flow collection and distribution work. When an emergency occurs, due to its own structural characteristics and the nervousness of the people to be evacuated, the evacuation efficiency of personnel is not high.

Hong [1] and others studied the game characteristics between "emergency events" and passengers. The concept of relative density was put forward, and the relationship between evacuation time and passenger flow, passenger flow speed, etc. was found. Lei [2] and others studied the influence of passenger density, exit width and automatic

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ticket gates on evacuation time using an agent-based evacuation model. The research results will help guide the evacuation design of large underground spaces. Lo [3] and others studied the influence of multi-exit evacuation mode and time by the interaction of evacuated crowds, and based on this, proposed an evacuation exit game theory choice model. Wang [4] and others studied the revision of the social power model by considering the influence of peer interaction. An evacuation simulation was carried out in the waiting hall of Hangzhou Wulin Square subway station. Provide data support for emergency plan and emergency response.

In this paper, based on the game passenger flow distribution, combined with the actual situation of the Shenyang Olympic Sports Center subway station, the design points of the evacuation plan and the construction process of the simulation model are given. Designed an evacuation plan for the Shenyang Olympic Sports Center subway transfer station. Use AnyLogic software to simulate and analyze the established emergency evacuation plan to get the emergency evacuation plan.

2 Analysis of Evacuation Plan

2.1 Determine Impedance

Scholars at home and abroad have studied the relationship between the speed, flow rate, and density of passenger flow through investigation and other means, and used SPSS software to fit the functional relationship between the three. This section conducts follow-up work on the basis of the analysis of the relationship between speed and density in the related literature [5] (Fig. 1).

Passenger speed-density fitting function inside the corridor:

$$v(\rho) = -0.596\ln(\rho) + 1.065 \tag{1}$$

Passenger walking speed-density fitting function inside the ascending stairs:

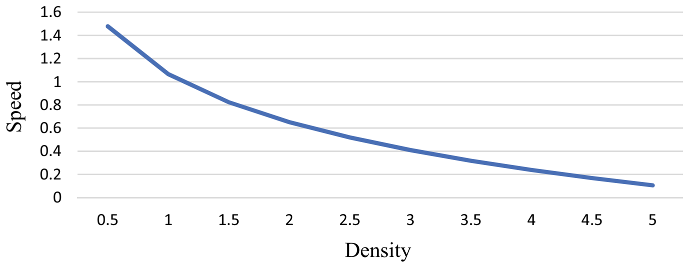

Fig. 1 Pedestrian speed-density curve in the passageway under congestion

$$v(\rho) = -0.360\ln(\rho) + 0.725 \quad (2)$$

Passenger walking speed-density fitting function inside descending stairs:

$$v(\rho) = -0.398\ln(\rho) + 0.813 \quad (3)$$

2.2 Multi-Passageway Game Passenger Flow Distribution Model

The development of the subway has made the internal environment more and more complicated. When distributing passenger flow in an emergency, it is necessary to take into account the passenger flow distribution among multiple OD pairs at the same time.

For any OD, define the effective evacuation route set R for passengers; there are k effective evacuation paths between OD pairs, namely $R = \{r_1, r_2 \ldots, r_k\}$; all the passenger flow between OD to be evacuated is allocated to the route r_k ($r_k \in R$), and the internal state of the station is $W = \{w_1, w_2 \ldots, w_n\}$ at this time. Under these conditions, the road network winning (evacuated passenger flow loss) matrix that can constitute a game problem [6]:

$$\begin{array}{c} \\ w_1 \\ w_2 \\ \ldots \\ w_n \end{array} \begin{array}{c} \begin{matrix} r_1 & r_2 & \ldots & r_n \end{matrix} \\ \begin{bmatrix} \alpha_{11} & \alpha_{12} & \ldots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \ldots & \alpha_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \alpha_{n1} & \alpha_{n2} & \ldots & \alpha_{nn} \end{bmatrix} \end{array}$$

a_{ij} is the time required for path j to travel when allocating passenger flow to path i. Known from game theory [7], if satisfied:

$$\max_i \min_j a_{ij} = \min_j \max_i a_{ij} = a_{rs}.$$

It shows that the game problem has a pure solution strategy. At this time, the corresponding strategy combination is called the Nash equilibrium of the game, that is, all the passenger flow is allocated to the path r. On the contrary, it shows that there is a mixed strategy solution. It is necessary to divide the passenger flow to be evacuated to various roads according to the obtained optimal ratio.

In reality, there is more than one evacuation route between the platform and the exit. When escaping, passengers will comprehensively consider the distance of different routes, time spent and other external factors, in order to achieve the shortest escape time and the highest efficiency.

People's path choice behavior will cause changes in the internal network impedance, and a game relationship is formed between the two [8]. The model believes that both travelers and road networks are wise. That is, after travelers have determined their "best route", the road network will increase congestion due to travelers' choices, resulting in prolonged evacuation time and achieving the goal of reducing passenger flow. When the two compromise, the dynamic balance is achieved, and the overall evacuation efficiency is the greatest. That is, after the passenger flow distribution plan, the impedance is the smallest, and the travel time of the route chosen by all the persons to be evacuated is the shortest.

2.3 Design Ideas of Subway Evacuation Scheme

Determine the internal information of the station. Comprehensively consider the multi-path between the evacuation point and the exit, determine the OD matrix, the total evacuation flow Q, and allocate the flow rate n in stages. Suppose the initial distribution flow in each facility is 0.

Get the set K_k of effective paths in the station's internal network. According to the observation data, using the Dijsktra algorithm, using time as the impedance, retrieve the OD path with the least impedance, find the path with the shortest travel time, and place the first batch of passengers into this path using all-by-nothing allocation.

After inserting the first batch of passenger flow, update the flow and travel time of each facility, and calculate the impedance change value. Based on the calculated impedance value, the Dijsktra algorithm is used to find the second shortest path. Establish the winning (loss) matrix, use the game distribution idea to carry out the evacuation distribution of passenger flow and solve it, and determine the flow proportion of the multiple paths allocated to each path.

When there are multiple paths, it is necessary to update the travel time of the facilities and sections, use Dijsktra again to find the third shortest path, and complete the previous steps until no new shortest path is generated.

Repeat the above steps to allocate all OD pairs until the distribution ratio of each path between each OD pair is obtained, the allocation is over, and the algorithm is completed.

2.4 Evaluation System

The evacuation time is the core measure of whether the plan is an effective plan for subway evacuation. According to the requirements of 8.3.10 in the "Metro Design Code" [9]: the total time from the first person to evacuate to the last person should be less than 6 min. Calculated as follows:

$$T = 1 + \frac{Q_1 + Q_2}{0.9[A_1(N-1) + A_2 B]} \le 6\,\text{min} \quad (4)$$

where

- T Evacuation time (s);
- Q_1 Number of passengers on the train (p);
- Q_2 Number of passengers and staff on the platform (p);
- A_1 Escalator capacity (p/(min × m));
- A_2 Stair passing ability (p/(min × m));
- N Number of escalators;
- B Stair width (m).

3 Design of Evacuation Plan for Olympic Sports Center Station of Line 9

3.1 Overview of Olympic Sports Center Station

Shenyang Metro Line 9 is 29 km long. There are 23 stations in total, all of which are underground stations. Among them, there are 4 transfer stations including Olympic Sports Center Station and Changqing South Street Station, and the remaining 19 are ordinary stations. The basic conditions such as the floor area and internal structure of the Olympic Sports Center Station match the game allocation model. At the same time, the internal passenger flow evacuation route is more complicated and typical, so this article chooses the Olympic Sports Center Station as the research object (Fig. 2; Table 1).

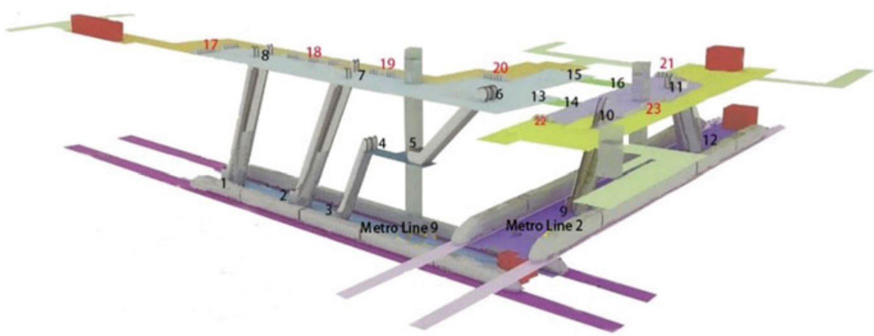

Fig. 2 Schematic diagram of the interior of the olympic sports center station

Table 1 Node division of the station

	Point
Starting point	1, 2, 3, 9 ,12
Intermediate point	4, 5, 6, 7, 8, 1, 13, 14, 15, 16
End point	17, 19, 21, 22

3.2 Passenger Flow Distribution Plan Design

3.2.1 Evacuation Plan in Case of Emergency on Line 9

Scenario simulation: A fire broke out when the train of Line 9 arrived in the Olympic Sports Center Station. Assuming that the subway is fully loaded with 1,300 passengers waiting to be evacuated, and the total number of platform workers is 200. At the same time, no trains on Line 2 arrived at the station, and trains arriving soon will not stop at the Olympic Sports Center Station (Fig. 3; Table 2).

(1) Impedance calculation: The calculation result is shown in the figure below, and the impedance unit is second.
(2) Determine the value of the number of allocations n: Here, n is set to 3, that is, the total passenger flow is divided into three times for distribution, and the number of passenger flows allocated each time is 500.
(3) The first allocation: First, an all-or-nothing allocation is performed, that is, all the first batch of 500 passengers will be allocated to the 2–7-19 route path with the least impedance. At the same time, the passenger flow of Line 2 is less, and the all-in-one evacuation is directly carried out.
(4) The second and third allocations: After each allocation is completed, the formula (1) (2) is used to determine the impedance value of each road section in the next

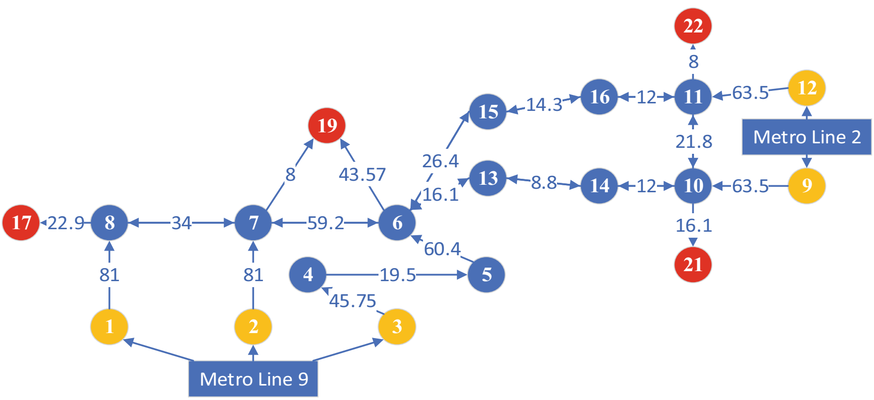

Fig. 3 The internal route impedance value of the station

Table 2 Effective evacuation path and impedance value

Number	Effective evacuation path	Impedance value
1	1-8-17	103.9
2	1-8-7-19	123
3	2-7-8-17	137.9
4	2-7-19	89
5	3-4-5-6-19	169.3
6	3-4-5-6-13-14-10-21	178.65
7	12-11-22	71.5
8	12-11-10-21	101.4
9	9-10-11-22	93.3
10	9-10-21	79.6

Table 3 Results of passenger flow distribution plan for platforms of line 9

Number	Effective evacuation path	Flow (p)	Percentage (%)
1	1-8-17	60	4
2	1-8-7-19	102	6.8
3	2-7-8-17	232	15.5
4	2-7-19	500	33.3
5	3-4-5-6-19	431	28.7
6	3-4-5-6-13-14-10-21	175	11.7

Table 4 Results of passenger flow distribution plan for platforms of line 2

Number	Effective evacuation path	Flow (p)	Percentage (%)
7	12-11-22	50	25
8	12-11-10-21	50	25
9	9-10-11-22	50	25
10	9-10-21	50	25

allocation under the congested state. According to the effective path, the winning (loss) matrix is established and then solved for distribution (Tables 3 and 4).

(5) Distribution result.

3.2.2 Evacuation Plan in Case of Emergency on Line 2

Scenario simulation: A fire broke out when the train of Line 2 arrived in the Olympic Sports Center Station. Assuming that the subway is fully loaded with 1,300 passengers waiting to be evacuated, and the total number of platform workers is 200. At

Table 5 Results of passenger flow distribution plan for platforms of line 2

Number	Effective evacuation path	Flow (p)	Percentage (%)
7	12-11-22	500	33.3
8	12-11-10-21	250	16.7
9	9-10-11-22	250	16.7
10	9-10-21	500	33.3

Table 6 Results of passenger flow distribution plan for platforms of line 9

Number	Effective evacuation path	Flow (p)	Percentage (%)
1	1-8-17	34	17
2	1-8-7-19	33	16.5
3	2-7-8-17	33	16.5
4	2-7-19	34	17
5	3-4-5-6-19	33	16.5
6	3-4-5-6-13-14-10-21	33	16.5

the same time, no trains on Line 9 arrived at the station, and trains arriving soon will not stop at the Olympic Sports Center Station.

Determine the value of the number of allocations n. Here, n is set to 3, that is, the total passenger flow is divided into three times for distribution, and the number of passenger flows allocated each time is 500 (Tables 5 and 6).

3.3 *Station Emergency Response Plan*

(1) Variable attribute equipment
According to the passenger flow distribution plan, when a subway arrives on Line 9 and no subway arrives on Line 2, the passages L13-L14 change the direction of passage to Line 2, and the influx of line 2 passengers into the passage is prohibited; the gates need to be fully open, and the opening direction is the outbound direction; the four pairs of escalators need to be stopped and used as stairs [10].

(2) Passenger separation point and concentration point
Separation point: According to the passenger flow distribution plan, guardrails are needed to divide the escalator into different escape routes at the left and right sides of the number 8, 7, and 6, so that the passenger flow at the above three points can only be passed on one side. Number 14 and 16 should adopt the principle of nearest evacuation and lead to exits 22 and 21. Prevent staying, catching up, and congestion.

Concentration point: On the one hand, the number 2 escalator needs to be stopped and used as a staircase. On the other hand, a 2 m fence needs to be installed at the entrance of the escalator to make full use of the entrance space (Fig. 4).

Reference number 13 is a one-way entrance. Compared with 15, the distance between the two is only 10 m, but the design in the evacuation plan is to give priority to the use of passage way 13. Appropriately flow the number of passengers from 13 to 15, and try to maintain a free flow state to ensure that the overall passage time of the passage is minimized (Fig. 5).

(3) Platform, station hall area

Platform: The partition method shall be adopted between the number 1, 2, and 3 escalators. When evacuating, passengers in the carriage should choose the nearest stairs to escape, which is more in line with the actual situation. This can effectively prevent the occurrence of convection.

In the station hall on the first floor, it is necessary to guide the crowd, that is, use guardrails and manual on-site command methods to restrict the flow direction of the evacuation passenger flow to prevent large-scale interweaving and convection phenomena.

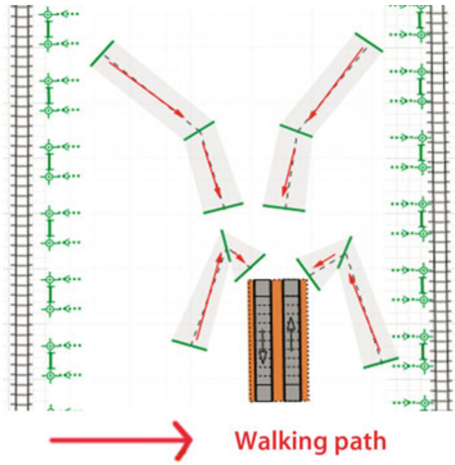

Fig. 4 Schematic diagram of optimization measures at the entrance of the stairs

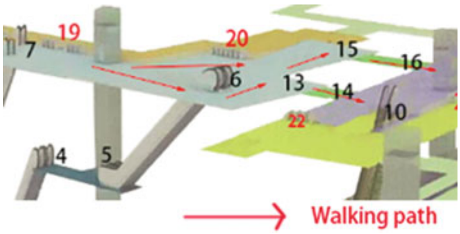

Fig. 5 Schematic diagram of crowd path

Combined with the evacuation plan, people evacuated through elevator No. 8 will use gates 17 and 18 to evacuate; people evacuated by elevator No. 7 use gates 18 and 19 to evacuate; people evacuated by elevator No. 6 use gates 20 and 22 to evacuate; Passengers evacuated from channel 13–14 use gate 22 to evacuate, and passengers evacuated from channel 15–16 use gate 21 to evacuate.

Station hall: Passengers who have reached the outside of the gate can be regarded as completed evacuation. Although these passengers have reduced their risks, they still need to be guided. Therefore, in the station hall on the first floor of Line 9, guardrails and evacuation signs are used to guide passengers passing through the turnstiles to use the nearest exit to escape to the ground.

4 Anylogic Simulation and Evaluation

4.1 Simulation Environment Construction

This simulation included the construction of the plane frame of the Olympic Sports Center Station, the layout of basic attributes (flow, passage, etc.), simulation parameter setting, allocation plan placement, running simulation, and effect evaluation (Fig. 6).

Simulation parameter setting regulations:

(1) The generation rate of passenger flow is 20p/s
(2) The free flow travel time in the emergency state is set to the maximum value in the free flow state, and the travel time of the crowded passenger flow is determined according to (1)–(3).

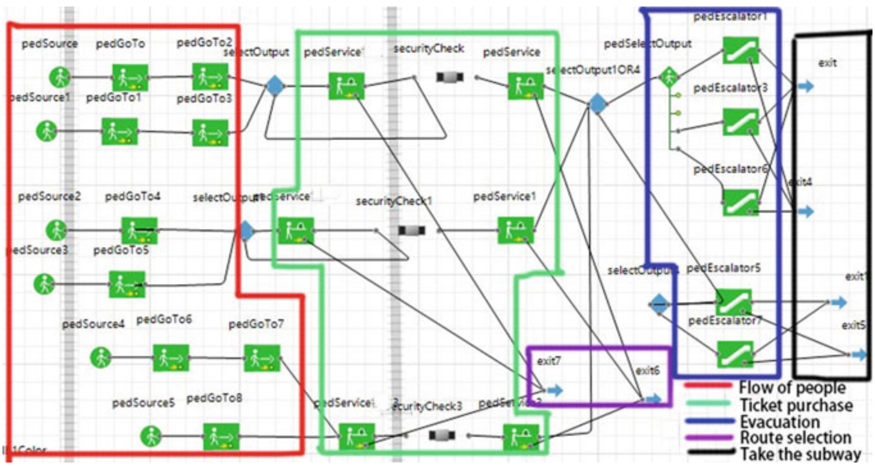

Fig. 6 Crowd flow model construction

(3) The proportion of traffic allocated for each path is determined according to the game distribution result.

4.2 Evaluation of Evacuation Plan for Olympic Sports Center Station

(1) Theoretical calculation:
1500 people to be evacuated at Olympic Sports Center Metro Station, escalator capacity 100 p/(min × m), 4 escalators, staircase passage capacity 60 p/(min × m), staircase width 3 m, calculated by 2.6 formula, theoretical evacuation time 232 s.

(2) After taking measures:
According to the game distribution plan, the direction of the flow of people is divided, and the number of results is put into the simulation software. According to the relevant requirements of emergency evacuation, measures such as path restrictions and guardrails are adopted in the software to divide the internal route of the passage and conduct simulation experiments (Fig. 7).

After the simulation, the interweaving phenomenon on the west side of the station hall has been significantly improved. The U-shaped crowd gathering area has also been relieved. The crowd density color in all passages has dropped by one level, and the purpose of crowd evacuation has become clearer. The simulation results show that the overall loss time of evacuation is reduced, the maximum density in the facility is reduced, and the final evacuation completion time is 208 s (Fig. 8).

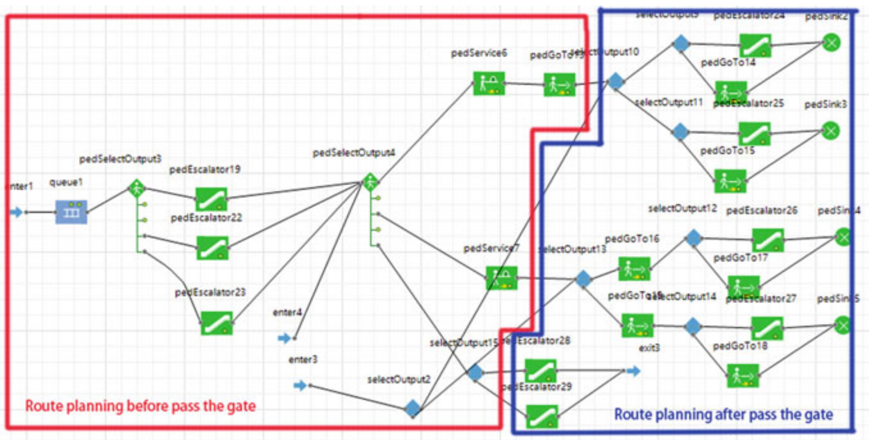

Fig. 7 Schematic diagram of the evacuation process path of Line 9

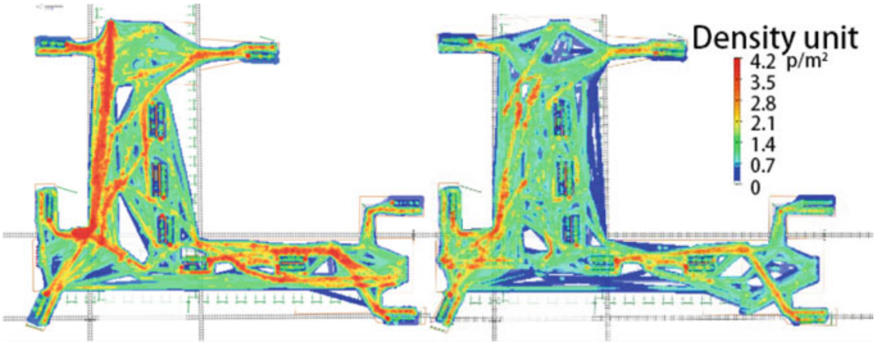

Fig. 8 Comparison diagram of measures taken and no measures taken

5 Summary

This paper takes Shenyang Metro Line 9 and Olympic Sports Center Station as the research background. Combining the established theoretical model and research data, this paper focuses on platform network construction, route retrieval, data collection, game distribution, and emergency response. This article takes Shenyang Metro Line 9 and Olympic Sports Center Station as the research background. Combining the established theoretical model and research data, this article focuses on platform network construction, route retrieval, data collection, game distribution, and emergency response. A specific evacuation plan for Line 9 has been worked out. Simulate demonstration through Anylogic simulation. Taking the evacuation time as the first priority, the route plan of Line 9 during the evacuation was optimized, and the rationality of the plan was verified. Finally, a design plan was proposed.

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