

Study on Optimization of Passenger Flow at a Metro Station Based on AnyLogic—Case Study of Youfangqiao Station of Nanjing Metro Line 2

Weihong Ni, Jiahao Yu, Hong Cai, Meimei Bai*, and Bin Wu

Abstract: In this study, simulation software AnyLogic was used to establish a station simulation model for a metro line. First, a basic model of the environment of the metro station was drawn, and accordingly, reasonable assumptions and simplifications were proposed. Then, a diagram of the passenger walking path was created and the simulation variables and functions for passenger flow management were designed. Considering Youfangqiao Station of Nanjing Metro Line 2 in China as an example, the real passenger flow data of this station were statistically analyzed. To simulate the station passenger flow management, input parameters such as the passenger space diameter, passenger flow generation rate, delay rate of automatic fare collection equipment and security check machine, and the number of gates were considered. Passenger flow management was optimized for the morning and evening peak periods, and reasonable suggestions were proposed based on the optimization results, providing a theoretical basis for the construction planning and pre-evaluation of station operation capacities of urban rail transit systems.

Key words: metro; passenger flow management; pedestrian; AnyLogic

1 Introduction

The urban metro system in China has entered a period of rapid development. As an important means and effective method for alleviating urban traffic congestion, the metro has gained considerable attention from many viewpoints. Therefore, determining how to scientifically and rationally set up station equipment and coordinate passenger flows in different environments is critical to the management of metro stations in the face of short-term peak passenger flows.

Most of the existing research on the passenger flow management of stations was conducted from the perspective of operation. There have been few

systematic and quantitative studies from the perspective of passengers. In an early field study, Older^[1] found that changing the locations of different facilities had a serious impact on the pedestrian flow route. Modak and Patkar^[2] proposed changing the layout of the internal structure of a station to improve the efficiency of pedestrian distribution and reduce passenger flow confusion at the station. Melkote and Daskin^[3] established a general model for optimizing the layout of facilities at a station, thereby making the subject of design layout more specific. Li and Zhou^[4] established a simulation model for passenger organization during peak periods, proposed an evaluation index and evaluation method for the simulation results, and proposed a basic concept for passenger organization simulations. Wang^[5] summarized the principles of passenger flow management at stations and formulated the corresponding passenger flow management measures by analyzing various examples of internal space structures, station service equipment, and facility layouts of stations. Li et al.^[6] determined passenger flow rules for a station and conducted risk

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identification using a Gaussian hybrid model to analyze data from the Shenzhen Metro.

In terms of pedestrian analyses, as early as 1971, Fruin^[7] conducted a detailed analysis of the traffic characteristics and spatial characteristics of pedestrians and proposed the concept of “service level”, thus laying the foundation for research on pedestrian traffic. Pushkarev and Zupan^[8] summarized the relationships between pedestrians, buildings, and pavements from a macro perspective, focusing on traffic characteristics such as pedestrian density, pedestrian speed, and passenger flow. Helbing and Molnár^[9] considered the complexity of pedestrians and proposed a “Social Force Model” based on the formation of multiple social forces. Nikolić^[10] determined the relevant characteristics of pedestrian flow (such as the time for movement and required space) based on field data collection at railway stations, aiming to study the qualitative and quantitative properties of pedestrian behavior.

In this study, the social force model was employed to investigate passenger flow management. Through field monitoring and sampling, the basic characteristics of passenger travel and the behavioral responses of passengers in face of a large number of passengers were investigated, and the data of passenger behavior characteristics in different passenger flows were analyzed. Youfangqiao Station of Nanjing Metro Line 2 in China was considered as an example. AnyLogic simulation software was used to construct the structure of the metro station, and conduct the simulation research by changing simulation parameters such as the speed of security check, the number and the running speed of automatic fare collection equipment.

2 Construction of Metro Station Simulation Model

2.1 AnyLogic software

A computer can calculate the relationships between independent variables and dependent variables. However, if time constraints are applicable, using a static model for a deterministic environmental analysis is impracticable. Advances in computer technology have enabled the creation of several dynamic models. Common dynamic models include cellular automata model, magnetic model, and social force model^[11]. However, the adaptability of cellular automata model is not enough, and magnetic model ignores the psychological factors of pedestrians. Social force

model believes that the behaviors of passengers are determined based on their self-driving forces and the parameters of practical significance, and it can more truly describe the behaviors of passengers. Because passengers are the research subject of this study and the passenger self-driving force of social force model can help the simulation object (i.e., the passenger) automatically make a route selection, and the social force model was chosen for modeling and simulation.

AnyLogic is a multisystem modeling and simulation program for agents and discrete events; it can overcome technical bottlenecks to support secondary development such as integrating HLA support in AnyLogic^[12]. The AnyLogic “Pedestrian Library” is an advanced library that uses variable parameters to simulate pedestrian traffic in real environments based on the social force model. The basic principle is that the movement of a pedestrian is affected by not only the pedestrian themselves but also external obstacles. The destination of the pedestrian is an internal factor, whereas the surrounding environment is an external factor. Both internal and external factors contribute to the driving forces of passenger movement; hence, the movement of passengers can be considered the result of the combined forces of the system^[13]. The AnyLogic Pedestrian Library includes environment modeling and behavior modeling. In this study, AnyLogic version 8.3 was used for modeling and simulation.

2.2 Simulation model of Youfangqiao Station

2.2.1 Basic environment of the metro station

As actual pedestrian movements arise from various purposes and needs, the simulation model cannot simulate all the details of passengers. Therefore, when establishing a simulation model, reasonable assumptions and simplifications are required. The assumptions and simplifications for this study are as follows.

(1) Area selection for simulation and analysis

The station hall is regarded as the background, and only the walking of passengers in the metro station hall is simulated without considering the platform and the external environment of the metro station.

(2) Assumptions and simplifications of station facilities

Because the escalator and stairs are located close to each other, the arrival locations for both are assumed identical, and agents are recovered at the same target line (i.e., passengers enter the platform at the same location). Further, some facilities at the station (e.g.,

garbage bins and temporary police points) are not considered owing to their smaller area relative to the station hall.

(3) Size simplification of the station structure

When drawing the basic environment model, owing to the limitations of the software itself, it is impossible to simulate the environment of the metro station at a scale of 1:1. Therefore, in the model of the metro building environment, the station hall was set to be 60 m long and 20 m wide with a middle area (200 m²), including gates, walkways, and security inspection machines (SIMs). AnyLogic software was used to draw the basic simulation environment at a ratio of 1:19.

The basic environment after the drawing is shown in Fig. 1. The left half is the north station hall and the right half is the south station hall.

In this software, the tool “wall” is used to draw the boundaries of subway stations, guide rods, etc. The tool “rectangular wall” is used to draw areas where passengers cannot walk, such as columns and ticket booths. The sources and destinations of passengers are set using the “target line”. The tools “line service” and “regional service” are used to calibrate the numbers, locations, and queues of service facilities. Gates, SIMs, automatic ticket vending machines (TVMs), and other equipment can be displayed on the top level of the three-dimensional view.

2.2.2 Creation of the passenger walking path map

The goal of the passengers is to arrive at the target line

to leave the station or board the metro train. Different goals of the passengers determine their walking paths; based on these paths, the passenger walking path map can be created. Passengers enter the station hall from entrances 1 and 2 and choose from three payment methods: TVM, integrated circuit card, or mobile payment. Passengers from entrance 1 who need to buy tickets go through the station hall walkway to the TVMs near entrance 2. After purchasing the ticket, passengers with packages need to get their packages checked by the security check machine. After the security check, they enter the station through the gate after a successful examination of the ticket. Passengers access the platform through the stairs and escalators and wait for the metro train. After the train stops at the station, the passengers who wish to board the train complete the boarding process. The passengers who disembark the train enter the station hall through the stairs and escalators and complete the exit process after their tickets are checked. The inbound and outbound processes of passengers must be combined with the basic environment, as shown in Fig. 2.

The controls in the Pedestrian Library of the simulation software were connected to realize the inbound and outbound processes. Related controls include pedSoure, pedGoTo, pedService, and pedSink. The walking path of the inbound passenger flow is shown in Fig. 3.

To clearly understand the passenger density and the

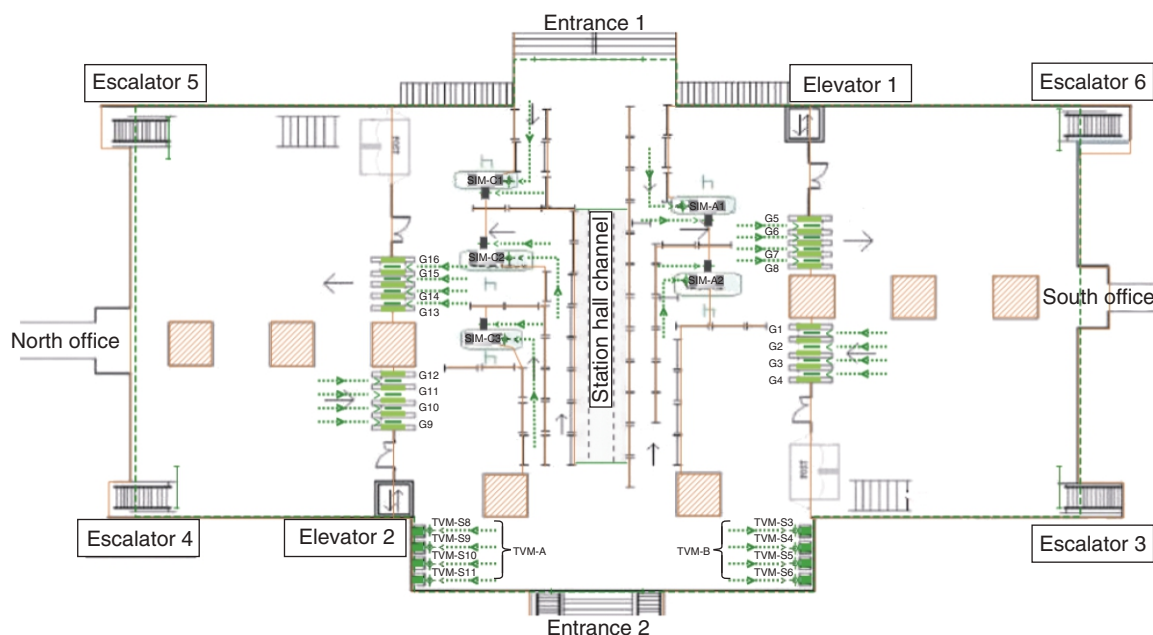


Fig. 1 Basic environment rendering.

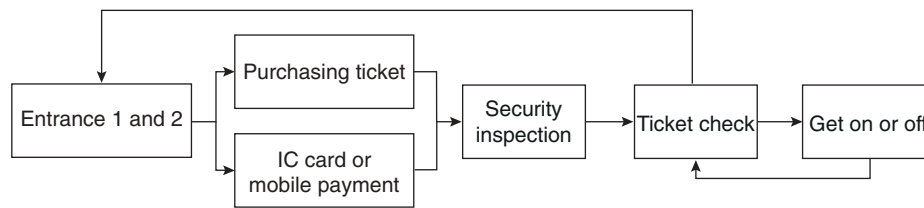


Fig. 2 Chart of the inbound and outbound processes of passengers.

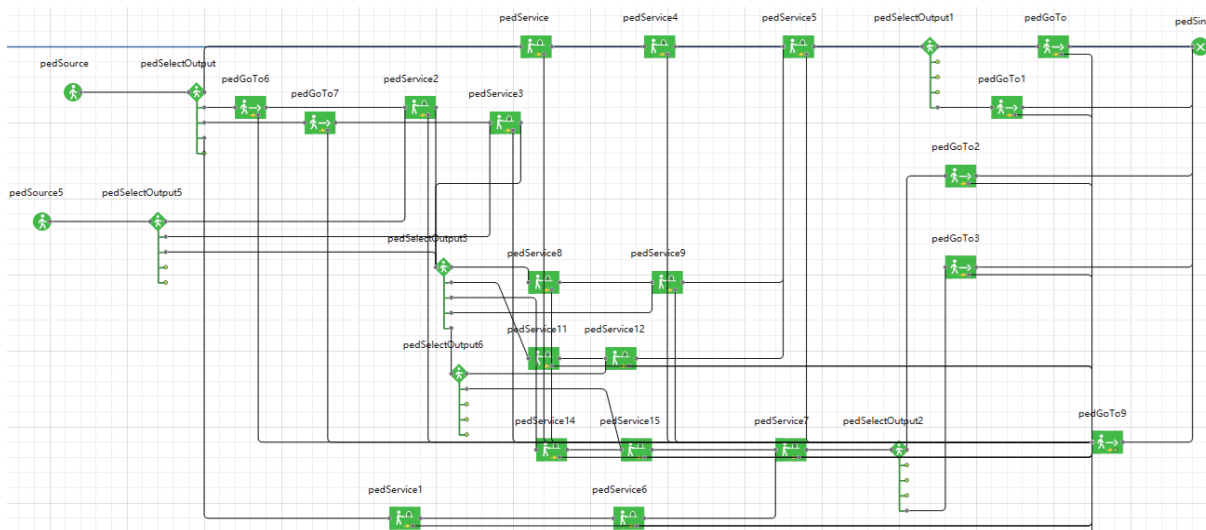


Fig. 3 Walking path of the inbound passenger.

total number of people in the station hall dynamically, the passenger library tool is used to set up a heat map, which is displayed dynamically at runtime. The density of people per square meter is expressed using colors on the heat map. Red represents passenger congestion, and blue indicates that there is no crowd.

3 Passenger Flow Management Optimization at Youfangqiao Station

3.1 Current situation of passenger flow management at Youfangqiao Station

Youfangqiao Station currently uses an automatic fare collection (AFC) system that is commonly employed for urban rail transit operations; this system mainly comprises a central computer, an encoder/sorter, a TVM, a card vending machine, and a gate.

In this study, the real passenger flow data of Youfangqiao Station in May 2019 were selected, as shown in Table 1.

3.1.1 Simulation parameter design

(1) Pedestrian space and walking speed

The pedestrian space has static and dynamic parts. The static space refers to the size of the space occupied by people on the horizontal plane under static

conditions. The dynamic space mainly comprises the stride area, visual area, sensing area, and avoidance and response area^[14]. Passengers can choose the most comfortable traveling speed as the expected speed according to their travel purpose, physical fitness, and other factors without interference from other people. Based on the statistical analysis results obtained from a large amount of data from domestic and international studies, a system-set value was used to set the initial speed as a random value in the interval range [0.3, 0.7] (m/s), the comfortable speed as a random value in the interval range [0.5, 1] (m/s), and the pedestrian space diameter as a random value in the interval range [0.4, 0.5] (m).

(2) Path selection probability setting

To identify the trends of passengers entering from the two entrances and the probability of each piece of equipment being selected, a field sampling survey method was used. For entrance 2, from the camera monitoring data of the station hall, we obtained the values given in Table 2.

Because the number of people choosing machine 1 and machine 2 was extremely small, it could be ignored. The probabilities of passengers from entrance 2 choosing SIM-C3, SIM-C2, SIM-A2, TVM-A, and

Table 1 Passenger flow statistics of Youfangqiao station (May 2019).

Date	Passenger flow category													
	Morning peak passenger flow							Evening peak passenger flow						
	Inbound passenger flow			Outbound passenger flow				Inbound passenger flow			Outbound passenger flow			
	Proportion of core period		7:00–9:00	Proportion of core period		17:00–19:00	17:30–18:30	Proportion of core period		17:00–19:00	Proportion of core period		17:30–18:30	18:30
	7:30–8:30	8:30		7:30–8:30	8:30			7:30–8:30	8:30		7:30–8:30	8:30		
May 1st	Wed.	6125	3272	53.42%	1012	505	49.90%	1866	976	52.30%	5092	2715	53.32%	2719
May 2nd	Thur.	5318	2877	54.10%	964	435	45.12%	1632	800	49.02%	5061	2696	53.27%	22992
May 3rd	Fri.	5318	2877	54.10%	964	435	45.12%	1632	800	49.02%	5061	2696	53.27%	22765
May 4th	Sat.	5606	3191	56.92%	1007	513	50.94%	2006	991	49.40%	5154	2738	53.12%	22851
May 5th	Sun.	13310	8724	65.54%	1433	798	55.69%	1670	888	53.17%	8428	4525	53.69%	27965
May 6th	Mon.	14163	9114	64.35%	1367	795	58.16%	1693	902	53.28%	8758	4351	49.68%	28584
May 7th	Tues.	14182	9143	64.47%	1359	750	55.19%	1756	875	49.83%	8683	4600	52.98%	28633
May 8th	Wed.	14123	9385	66.45%	1377	799	58.02%	1742	940	53.96%	8549	4554	53.27%	28674
May 9th	Thur.	5318	2779	52.26%	869	508	58.46%	1666	790	47.42%	5061	2665	52.66%	23654
May 10th	Fri.	13893	8866	63.82%	1323	741	56.01%	2082	1108	53.22%	8768	4551	51.90%	29734
May 11th	Sat.	7491	4269	56.99%	1181	579	49.03%	2268	1202	53.00%	8065	3131	38.82%	26389
May 12th	Sun.	5620	3117	55.46%	1026	529	51.56%	1966	938	47.71%	4840	3567	73.70%	23245
May 13th	Mon.	14045	8931	63.59%	1357	812	59.84%	1450	768	52.97%	8838	4563	51.63%	27904
May 14th	Tues.	13856	9033	65.19%	1274	746	58.56%	1599	843	52.72%	8673	4546	52.42%	27829
May 15th	Wed.	13970	9036	64.68%	1253	716	57.14%	1602	860	53.68%	10073	4517	44.84%	28151
May 16th	Thur.	14069	8975	63.79%	1375	287	20.87%	1622	886	54.62%	8339	4386	52.60%	28391
May 17th	Fri.	13955	8999	64.49%	1292	741	57.35%	1921	1030	53.62%	8297	4329	52.18%	29332
May 18th	Sat.	7321	4139	56.54%	1106	489	44.21%	2184	1059	48.49%	5636	2884	51.17%	26547
May 19th	Sun.	5540	3017	54.46%	965	494	51.19%	1929	966	50.08%	5128	3641	71.00%	23850
May 20th	Mon.	13813	8940	64.72%	1436	819	57.03%	1864	982	52.68%	8401	4397	52.34%	29044
May 21st	Tues.	14126	9316	65.95%	1216	716	58.88%	1590	821	51.64%	8640	4521	52.33%	28341
May 22nd	Wed.	12883	8051	62.49%	1301	750	57.65%	1650	909	55.09%	8010	4278	53.41%	26802
May 23rd	Thur.	13856	9011	65.03%	1357	765	56.37%	1608	856	53.23%	7975	4185	52.48%	27859
May 24th	Fri.	13635	8897	65.25%	1319	784	59.44%	1983	1052	53.05%	8442	4210	49.87%	28703
May 25th	Sat.	7124	4024	56.49%	1060	481	45.38%	1731	785	45.35%	8096	2783	34.38%	22708
May 26th	Sun.	4728	2626	55.54%	716	334	46.65%	1780	882	49.55%	4143	2234	53.92%	19580
May 27th	Mon.	13800	9154	66.33%	1391	755	54.28%	1536	813	52.93%	8198	4560	55.62%	27388
May 28th	Tues.	13810	9104	65.92%	1342	789	58.79%	1590	884	55.60%	8133	4442	54.62%	27998
May 29th	Wed.	13717	8747	63.77%	1296	734	56.64%	1667	865	51.89%	8355	4296	51.42%	27888
May 30th	Thur.	13973	8691	62.20%	1253	711	56.74%	1535	761	49.58%	8174	4229	51.74%	27106
May 31st	Fri.	13534	8795	64.98%	1311	706	53.85%	1975	1071	54.23%	8126	4234	52.10%	28993

Table 2 Number of passengers from entrance 2 when choosing equipment.

Sample number	Number of passengers							Total
	Security inspection machine (SIM)-C3	SIM-C2	SIM-C1	SIM-A2	SIM-A1	Ticket vending machine (TVM)-A	TVM-B	
1	369	247	1	379	3	124	127	1250
2	385	263	2	383	5	133	129	1300

TVM-B were 0.3, 0.2, 0.3, 0.1, and 0.1, respectively. Similarly, the probabilities of passengers from entrance 1 choosing SIM-C1, SIM-A1, TVM-A, and TVM-B were 0.2, 0.2, 0.3, and 0.3, respectively.

Youfangqiao Station is used as a transfer station, and the proportions of nontransfer and transfer passengers were 0.8 and 0.2, respectively.

3.1.2 Simulation of the peak passenger flow

According to the data, the high passenger flow in the morning rush hour (7:30–8:30) was selected for analysis. Taking integer values, the number of inbound passengers per hour was approximately 10000 and the number of outbound passengers per hour was approximately 800. According to the proportions of the numbers of passengers from entrances 1 and 2, the inbound rates were set as 3500 and 6500 people per hour, respectively.

Similarly, the high passenger flow in the evening rush hour (19:30–20:30) was also analyzed. Taking integer values, the number of inbound passengers per hour was approximately 1200, and the number of outbound passengers per hour was approximately 4800. According to the proportions of the numbers of passengers from entrances 1 and 2, the inbound rates were set as 420 and 780 people per hour, respectively.

The parameters were set, and the simulation was run. The simulation results are shown in Fig. 4.

3.2 Simulation of peak passenger flow management optimization and analysis of results

3.2.1 Passenger walking path optimization and simulation

The results of the simulations show that although there are long passenger queues at the gates and SIMs in the nonpaid area (i.e., the spaces occupied by passengers before making the payment), there is no long-term stay of passengers in the paid area; moreover, the passengers cannot enter the platform. As the constructions of station hall are fixed, it is impossible to install additional gates to alleviate the peak passenger flows. Two-way gates can change the walking paths of passengers according to the needs of entering and exiting the station, thereby reducing the

passenger flow pressure before the gate, accelerating the passengers, and reducing the queuing time. Accordingly, the following modifications were made.

During the morning peak period, the two adjacent outbound gates of each array are changed into the inbound mode; that is, G12/G11 and G1/G2 are changed into the inbound mode, thereby increasing the number of inbound gates and changing the walking paths of the passengers. Thus, the positions of the guide rods in the station hall are adjusted to segment the passenger flow and make the walking path clearer. Similarly, during the evening peak period, the two adjacent inbound gates of each array are changed into the outbound mode; that is, the G13/G14 and G7/G8 are changed into the outbound mode. The path optimization of the north station hall during the peak period is shown in Fig. 5; the path optimization of the south station hall is the same.

The passenger flow simulation results during the peak period after path optimization are shown in Fig. 6.

3.2.2 Optimization and simulation of AFC equipment passing rate

According to the previous simulation heat map, there is dense inbound passenger flow during the morning rush hour in the areas of the TVMs and SIMs.

Staff can be arranged to provide guidance near the TVMs to expedite ticket purchases and reduce ticket queuing. Then, based on field sampling survey statistics, the probabilities of passengers from different entrances choosing machines under the guidance of staff can be estimated. In particular, the probabilities of passengers from entrance 1 choosing TVM-A, TVM-B, SIM-C3, SIM-C2, and SIM-A2 are 0.05, 0.05, 0.35, 0.2, and 0.35, respectively; the probabilities of passengers from entrance 2 choosing TVM-A, TVM-B, SIM-C1, and SIM-A1 are 0.05, 0.05, 0.45, and 0.45, respectively.

To accelerate the security inspection process, passengers' small packages can be checked using handheld security inspection instruments. A sampling of the time data of 300 people in the field revealed that the optimized security inspection time was 0.5 s less than that before optimization. Therefore, the passing

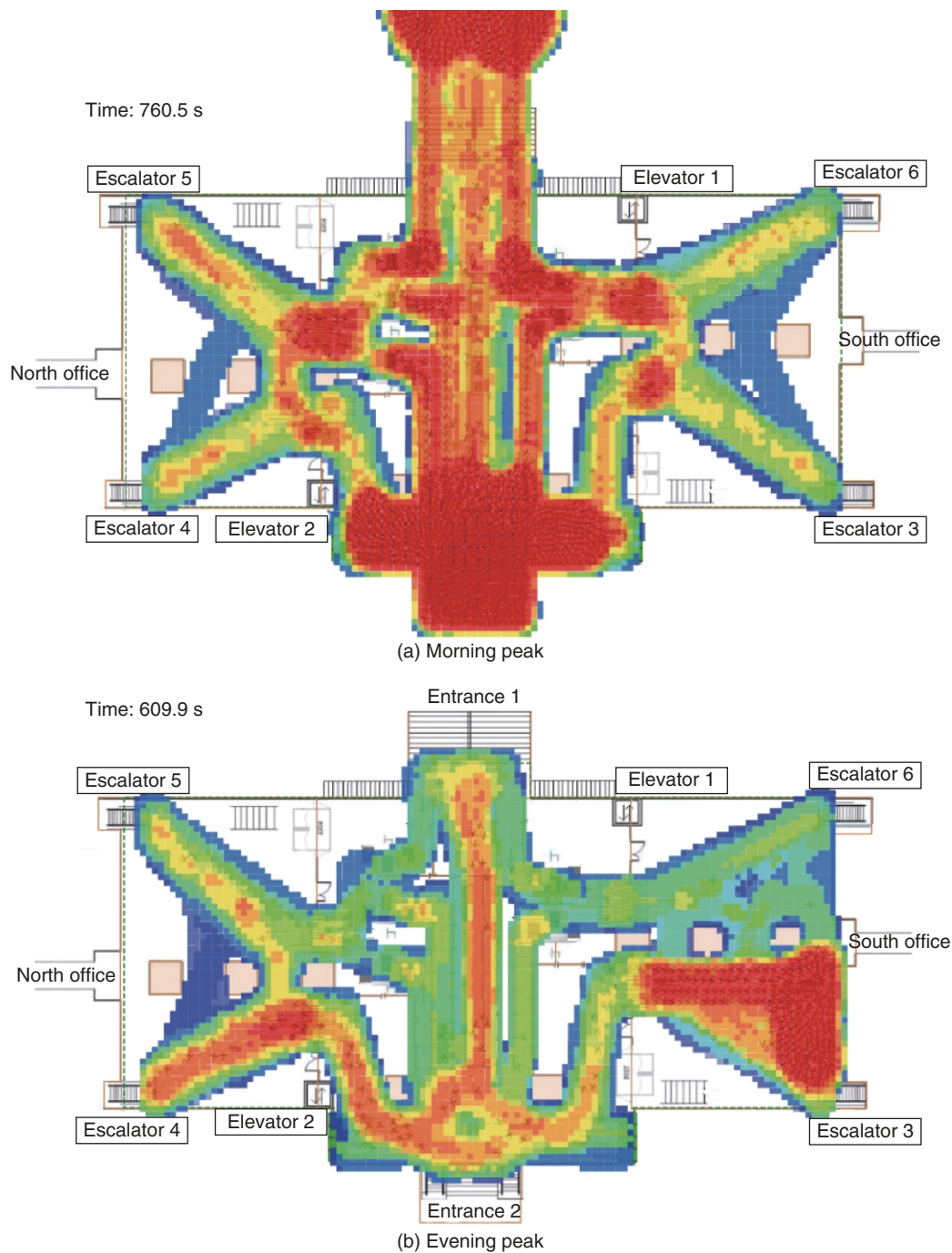


Fig. 4 Simulation results of peak passenger flow.

rate for the SIM in the model was set as a random value in the interval $[1.5, 2.5]$. The simulation result is shown in Fig. 7.

3.2.3 Analysis of simulation and optimization results

The morning peak passenger flow of Youfangqiao Station is concentrated between 7:30 and 8:30. Because the station hall was constructed relatively early and its area is fixed, there is no possibility of adding AFC equipment. Therefore, the pressure on the gates can

only be alleviated by managing the speed of the passenger flow entering the station. The two-way gate mode can be used to change the outbound mode to the inbound mode to ease the pressures of passenger flows. In addition, staff positions can be added to the morning peak hours for actively guiding passengers. If the passenger flow far exceeds the load capacity of the station, for the safety of subway operations, staff must be assigned to ensure timely responses to emergencies.

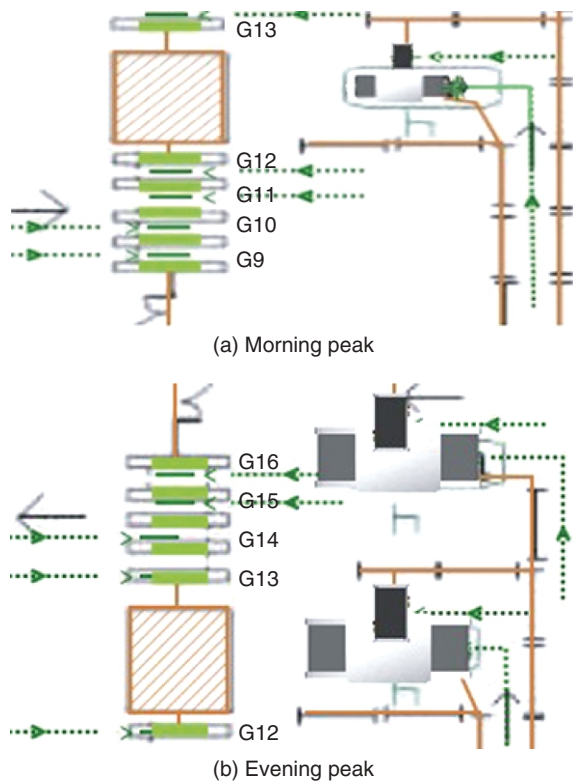


Fig. 5 Optimized path for peak passenger flow of the north station hall.

The evening peak passenger flow of the station is concentrated between 17:30 and 18:30 and is much less compared with the morning peak passenger flow. Moreover, passengers only need to pass the gates to complete the exiting process. The simulation results show that changing the gate mode to adjust the walking paths of passengers is sufficient for alleviating the passenger flow.

3.3 Suggestion

Based on the analysis of the influencing factors of passenger flow management and the simulation results, the following suggestions are proposed for optimizing the passenger flow management of Youfangqiao Station.

(1) Improve the capacity of station facilities—Owing to the usage habits of passengers, the utilization and failure rates of some facilities are very high. Failure during a peak period will lead to very serious congestion. By determining the failure rates, related equipment parts can be replaced in advance to prevent failure and increase the passenger passing rate. In addition, enhancing the service level of the staff is necessary. Faulty AFC equipment should be reported for repair, and obstacles in the walking path should be

cleared sufficiently in advance of the peak period.

(2) Passenger flow management plans corresponding to different levels of passenger flow should be formulated for the stations. In one example, a “Class I passenger flow” means that the vehicles entering the station at this time cannot afford to carry all the passengers waiting at the station. In such a scenario, the station staff should manage the passenger flow in time, e.g., by slowing down the process of passengers from the station hall entering the platform. A “Class II passenger flow” refers to crowded queues of passengers in the paid area. In such a case, the station staff should guide passengers near the gates or change the modes of the gates to speed up the passage of passengers. A “Class III passenger flow” refers to long queues and/or long durations in the nonpaid area. The staff should immediately guide passengers into the station at the entrance and advise them to consider changing to other means of transportation.

(3) When the passenger flow exceeds the normal passenger flow of the metro and the traffic capacity of the station hall, arranging temporary safeguard measures at the entrance is necessary; the main goals are to manage the distribution of the passenger flow and ensure the operational safety of the metro.

4 Conclusion

The present research can provide theoretical guidance for alleviating the congestion of large passenger flows in stations during peak periods and scientifically solving the conflicts and confusion in passenger flow lines while providing guidelines for future subway station construction (including architectural design and facility configuration) and even urban rail transit planning. The conclusions are as follows.

(1) The metro is an important means of transportation, and a sharp increase in the passenger flow will inevitably put great pressure on the original AFC equipment in station halls, especially those stations that cannot add new equipment because of smaller areas. When the passenger flow is within the acceptable range of the AFC equipment, the pressure on passenger flow management can be alleviated by correctly planning the passenger flow directions in the station hall, for example, by adding guide rods.

(2) With an increase in the passenger flow, the utilization rate of the AFC terminal equipment, especially the gates, increases sharply. When the passenger flow is very high, passengers will be

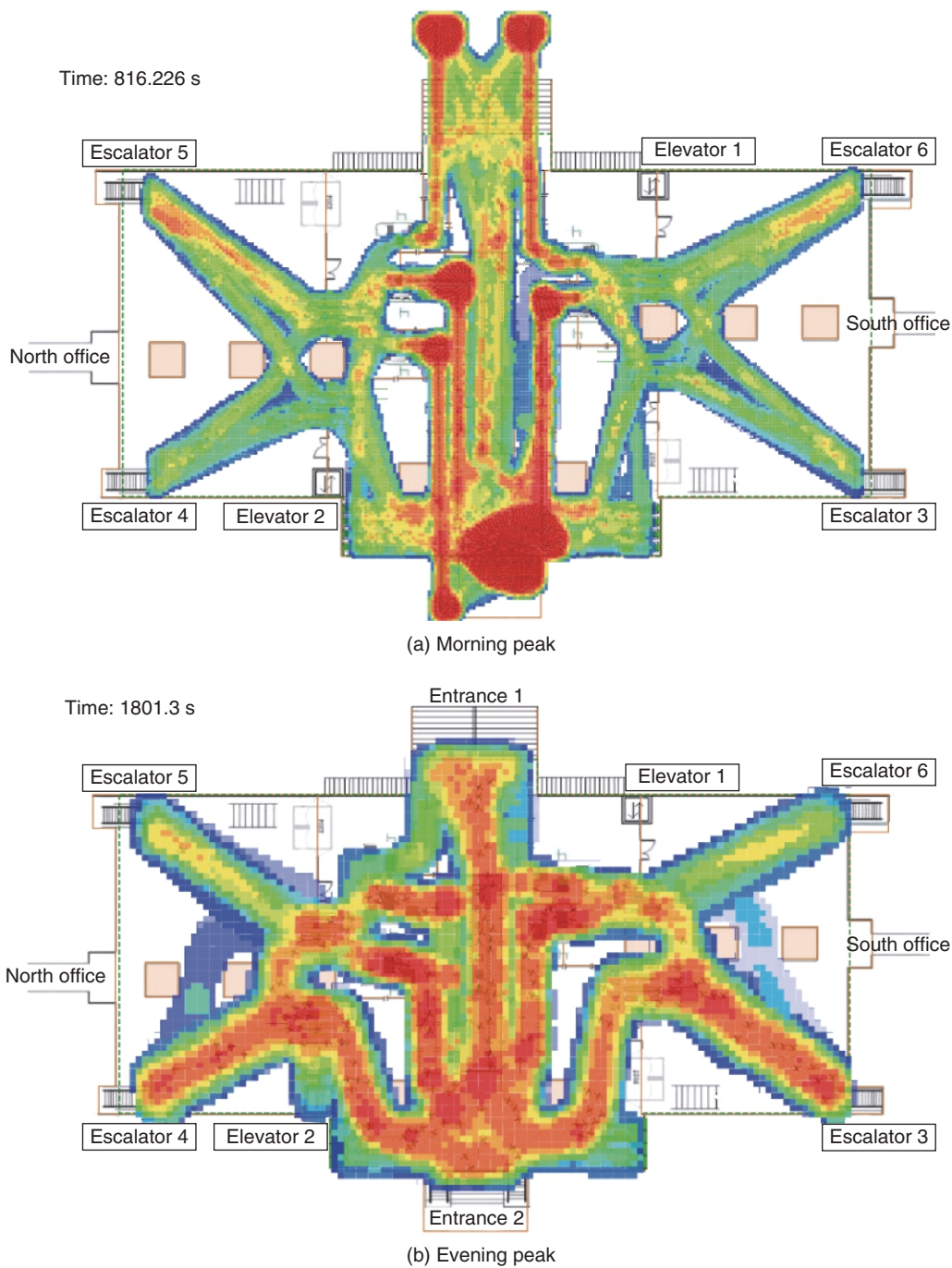


Fig. 6 Simulation results of peak passenger flow after optimization.

stranded in the station hall. Then, the number of people queued up in the ticket inspection area will increase, thereby increasing the time required for passengers to board. The passenger flow through the gates per unit time increases with an increase in the number of gates, and the passenger flow ultimately reaches a dynamic balance. Hence, an increase in passenger flow should be tackled by effectively managing the number of gates.

(3) During the morning rush hour, the traffic efficiency of passengers can be improved by increasing the number of inbound gates. However, in some cases, the tradeoff between the continued increase in the passenger flow and the inability to increase the number of inbound gates still imposes unreasonable pressure on the station hall. Although the passenger flow during the evening rush hour also increases, the flow is not as dense as that in the morning rush hour, and passengers

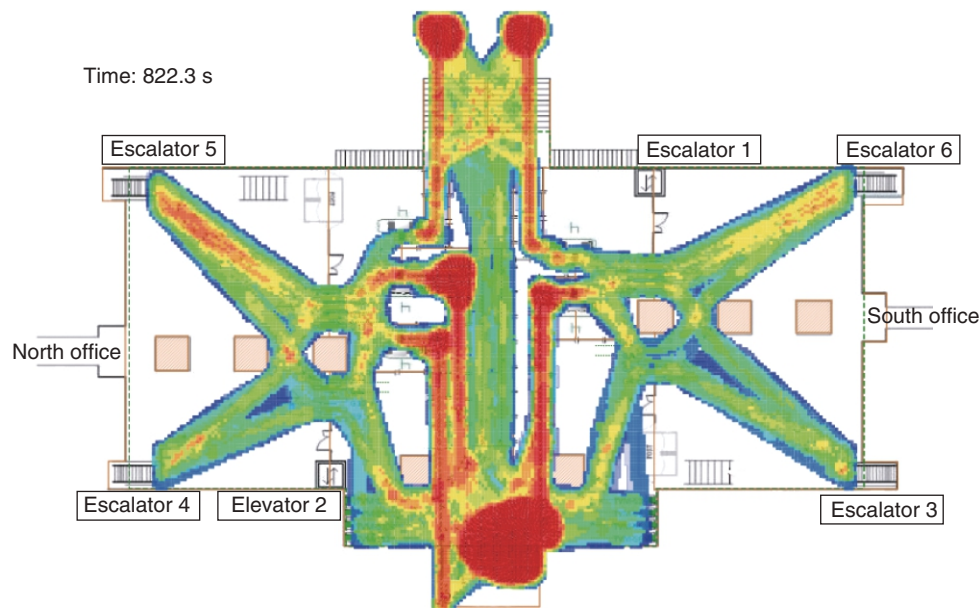


Fig. 7 Simulation result of morning peak passenger flow after optimization adopting AFC.

only need to check their tickets through the gates to leave the station. Therefore, during the morning peak period, staff can be added to guide passengers to operate the related equipment in the station hall to speed up ticket purchases, security inspection, and entry.

This study is restricted by the limitations imposed by many factors. For example, in the simulation, only the behavior of a single passenger is considered, without considering the speed of people when they walk together. Thus, the simulation results will have a small amount of error. In addition, in future work, the assumptions and simplifications of the model should be examined using several statistical tests to establish a more realistic simulation model.

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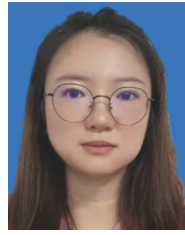
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