Research on the Renovation of Comprehensive Hub Stations and Passenger Flow Dispersal Based on Queuing Theory

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Abstract. With the increasing population density in popular cities and the surge in new tourist flows driven by short-video platforms, passenger volumes at major high-speed rail hubs have risen continuously, especially during holidays, posing challenges for emergency evacuation. Taking Beijing South Railway Station as a case study, the turnstile area in the subway transfer zone was identified as the primary bottleneck, where pseudo-queuing phenomena occur. Queuing theory was applied to model the system, with the number of turnstiles as the key optimization variable to reduce evacuation time. The results show that increasing the turnstiles to 12 reduces the evacuation time from 350.74 seconds to 317.94 seconds, a significant improvement of approximately 9.4%. The theoretical predictions align well with simulation results, with errors ranging from 1.91% to 4.99%. This model provides valuable insights for the emergency design and renovation of comprehensive transport hubs.

Keywords: Passenger flow evacuation, Queuing theory, Engineering renovation, Anylogic, Large passenger flow

1 Introduction

With the acceleration of urbanization and the rapid growth of passenger flow, integrated transportation hubs often face high passenger density during peak periods, especially during holidays and emergencies. Due to their complex spatial structure and concentrated passenger movement, such hubs are highly vulnerable to congestion and evacuation risks. To improve evacuation safety, many scholars have used simulation software and optimization algorithms to analyze emergency scenarios, identify bottlenecks, and propose improvement measures.

Existing studies have mainly focused on evacuation simulation and bottleneck analysis in metro stations and airport terminals. Chen Leiyu et al. [1], Wu Shuang et al. [2], Liu Jiaming and Zhao Liqiang [3], Zhou Bailing et al. [4], and Feng Qian et al. [5] used simulation methods to identify congestion points and optimize evacuation efficiency under large passenger flow conditions. Lopez-Carmona et al. [6] proposed a behavioral optimization model for crowd evacuation, while Fan Guiming and Chen

J. Zhang et al. (eds.), *Proceedings of the 2026 2nd International Conference on Engineering Management and Safety Engineering (EMSE 2026)*, Advances in Engineering Research 300,
https://doi.org/10.2991/978-94-6239-703-3_14

Lin [7], and Shen Jiaying [8] applied queuing theory to analyze congestion and predict evacuation time.

These studies provide valuable theoretical support. However, for comprehensive transport hubs with multi-modal passenger flow, research on emergency evacuation under holiday-related large passenger flow remains insufficient, particularly in terms of identifying critical passage capacities and quantitatively evaluating optimization measures. Therefore, this study takes Beijing South Railway Station as a case, combines queuing theory with AnyLogic simulation to model key congestion nodes, and uses gate configuration as an optimization variable to determine a reasonable capacity range, so as to provide quantitative support for emergency evacuation management in comprehensive hub stations.

2 Queuing Theory and Simulation Model Construction

2.1 Queuing Theory Model

The gate service system of the transfer area at the comprehensive hub station is modeled as an M/M/c queuing system.This model is adopted because the transfer gate area can be regarded as a typical multi-server queuing system in which passengers arrive randomly and are processed in parallel by multiple turnstiles. In order to simplify the theoretical analysis while maintaining engineering applicability, the following assumptions are made:

(1) Passenger arrivals at the turnstile area follow a Poisson process with an average arrival rate of λ\lambdaλ persons per second.

(2) The service time for each passenger at a single gate follows an exponential distribution, with an average service rate of μ people per second.

(3) The system contains ccc identical parallel turnstiles operating simultaneously.

(4) Passengers are served according to the first-come, first-served principle.

(5) Passenger reneging, balking, equipment failure, and overtaking behavior are not considered in the queuing process.

(6) Within the short-term evacuation period considered in this study, the arrival rate and service rate are assumed to be approximately stable, so the system can be analyzed under a quasi-steady-state condition.

2.1.1 Gate Utilization Rate. Utilization rate is an indicator for measuring the working intensity of the gate machines, representing the ratio of the working time of the gate machines to the total service time. It reflects the level of congestion of the gate machines,The formula is:

$$\rho = \frac{\lambda}{c * \mu} \tag{1}$$

λ represents the arrival rate of passengers at the gate area,people/s, μ represents the passage rate for each passenger through the security checkpoint,people/s per machine.

2.1.2 The Probability of no one Passing Through the Gate Machine. P_0 represents the probability that in a stable state, there are no passengers at all in the model (including the gate area and the waiting area), which is the probability that all the gates are in an idle state,The formula is:

$$P_0 = \left[\sum_{k=0}^{c\text{-}1} \frac{(\lambda/\mu)^k}{k!} + \frac{(\lambda/\mu)^c}{c!(1-p)} \right]^{-1} \tag{2}$$

c represents the number of gates in the main congested area,k is the summation variable, $c!$, $k!$ represents the mathematical correction factor.

2.1.3 Average Queue Length. The average queue length L_q refers to the average number of passengers waiting in the queue for passage, excluding those who are already passing through. The formula is:

$$L_q = \frac{(\lambda/\mu)^c \rho}{c!(1-\rho)^2} P_0 \tag{3}$$

2.1.4 Average Waiting Time. The average waiting time W_q refers to the average waiting time a customer spends in the queue from the moment they arrive at the gate until they pass through it. According to Little's Law[9], it can be derived from the average queue length:

$$W_q = \frac{L_q}{\lambda} \tag{4}$$

2.1.5 Average Duration of Stay. The average stay time Ws refers to the total average time that a passenger spends from the moment they arrive at the gate until they completely pass through the gate during the evacuation process. It is equal to the sum of the average waiting time and the average service time, and the formula is:

$$W_s = W_q + \frac{1}{\mu} \tag{5}$$

$\frac{1}{\mu}$ represents the average time taken for each passenger to pass through the security checkpoint

2.1.6 Theoretical Prediction of Total Time. During the daily operation, there will be no congestion at the gates. Therefore, a simulation of evacuation based on the normal passenger flow is conducted, and the output time is recorded as the normal evacuation time, denoted as T_{normal}. The sum of the normal evacuation time and the average waiting time of passengers is regarded as the theoretical predicted total time, denoted as $T_{\text{theoretical}}$, that is:

$$T_{\text{theoretical}} = T_{\text{normal}} + W_s \tag{6}$$

2.2 Construction of Simulation Model

2.2.1 Establishment of a Simulation Model of Beijing South Railway Station. This article takes Beijing South Railway Station as the research object. The B_1 transfer hall layer inside the station is approximately 300 meters in length and 110 meters in width. The central area of the B_1 transfer hall layer is approximately 80 meters in length and 60 meters in width. There are also multiple gate entrances in the central area of the layer. The B_2 and B_3 layers are the subway riding areas, with a width of approximately 10 meters and a total length of approximately 250 meters.The final model is shown in the Figure 1 below.

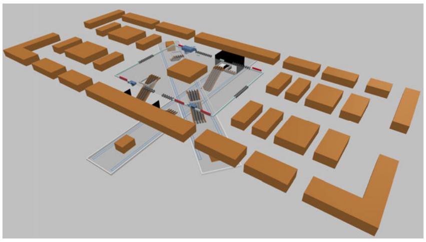


Fig. 1. Basic environmental maps of B_1, B_2, and B_3 levels of Beijing South Railway Station

2.2.2 Passenger Flow Analysis. During the simulation process, in order to accurately reflect the movement characteristics of different groups of people, different data parameters were set for each group. The specific data is shown in the Table 1 below.

Table 1. Typical Population Gait Data Parameters Table

Type of crowd	Effective occupation radius(m)	Walking speed(m/s)
Male	0.52	1.5
Female	0.50	1.4
Elderly person	0.58	0.9
Children	0.68	1.2
Passengers with luggage	0.45	1.3

For this experiment, the peak day at Beijing South Railway Station during the 2025 Spring Festival travel rush (February 4th) was selected, with an arrival volume of 248,000 people. Assuming that the passenger flow on this peak day is concentrated within 12 hours (from 6:00 to 18:00), the hourly arrival volume would be approximately 20,700 people. Therefore, the arrival rate of personnel in the simulation is set at 20,000 people per hour. Based on the above modeling and pedestrian data, it can be seen that the number of people in the station will fluctuate around 1100.

2.3 Creation of the Pedestrian Flow Diagram

Passengers arriving at the station enter the transfer hall from both sides of the B_1 floor. They select the appropriate transfer method based on their destinations. Based on the proportion of various transportation modes, a flowchart of pedestrian flow organization has been drawn, as shown in the Figure 2.

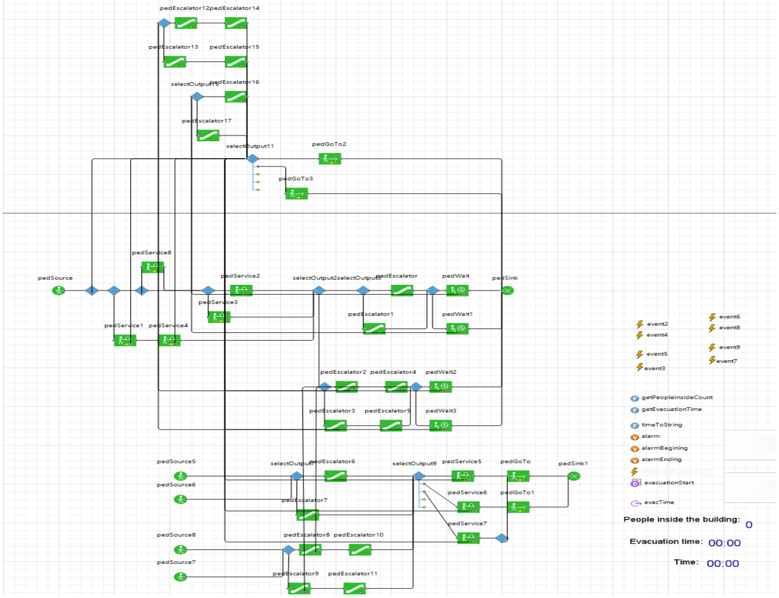


Fig. 2. Passenger walking logic module within Beijing South Railway Station

3 Results

3.1 Analysis of Traffic Congestion Situation

After the modeling process was completed, the model was simulated to observe the main congestion points within the model. An analysis was conducted on these congestion points, which were caused by the congestion that occurred in the area near the gates during the evacuation process within a short period of time, as shown in the figure. Therefore, the number of gates should be increased. If the number of gates is increased excessively, it will inevitably lead to waste during non-congested periods. Thus, the maximum number of gates set for this experiment is 14.

3.2 Queuing Theory Computational Theory Time

All the calculation parameters are based on the measured data from the Anylogic simulation model. Through multiple simulation runs with an initial model where the number of ticket gates c is set to 9, the overall average arrival rate at the congested ticket gates was measured to be $\lambda = 3.2$ people/s, and the average service rate was $\mu = 0.333$ people/s per machine. Based on the above data, the evacuation times for different gate number schemes can be calculated, as shown in Table 2:

Table 2. The calculation results of key coefficients in the model

Number of gates	Gate utilization rate	P_0	L_q	W_q	W_s
9	1.067	Inf	Inf	Inf	Inf
10	0.961	0.000027	38.22	11.94	14.94
11	0.874	0.000044	5.85	1.83	4.83
12	0.801	0.000068	1.25	0.39	3.39
13	0.739	0.000099	0.33	0.10	3.11
14	0.687	0.000138	0.09	0.03	3.03

*Note: When the number of gates c = 9, the gate utilization rate exceeds 1, indicating that the model is in an unstable state. This suggests that the number of gates needs to be adjusted to address this risk.

The calculation results show that as the number of entrance gates increases, the average waiting time decreases significantly, and the rate of decrease gradually slows down. Although when the number of gates reaches 14, the average waiting time is further shortened by 0.07 seconds, the impact on the final evacuation time has become very small. Finally, the number of gates is set within the critical range of 10 to 13.

To obtain the evacuation time of the model when it is not congested, the experimental parameters were set as 9 ticket gates, a personnel arrival rate of 12,000 people per hour, and 50 experiments were conducted. The evacuation time of the simulation experiment was recorded as shown in Figure 3.

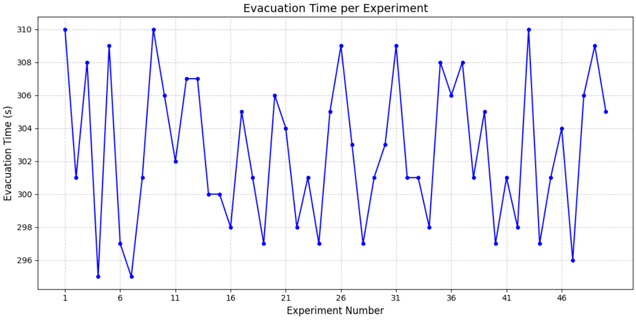
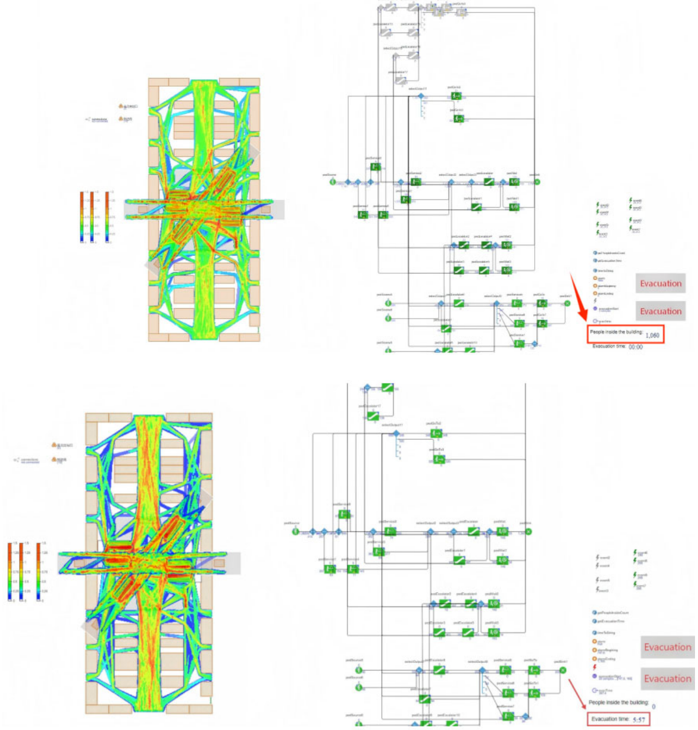


Fig. 3. Pedestrian evacuation time under uncongested conditions

The average of the 50 measured data was calculated to obtain the evacuation time under normal conditions, which was 305.68 seconds and was denoted as T_{normal}.

3.3 Anylogic Simulation Experiment

Based on the optimal number range of ticket gates derived from queuing theory, the simulation was conducted using Anylogic software. The operation logic of this model is that arriving passengers follow the pre-planned routes for transfer. When an emergency evacuation is needed, the evacuation button is clicked. People on different floors will go to the exit according to the nearest route. At the beginning of the evacuation, the system counts the number internally. When the last person reaches the exit, the evacuation is over and the evacuation time is obtained, as shown in Figure 4. When there are 9 ticket gates, the model's heat map and simulation screen are shown in Figure 5. When the optimal number of ticket gates is 12, the model's heat map and simulation screen are shown in Figure 6.



People inside the building: 1,060
Evacuation time: 00:00

People inside the building: 0
Evacuation time: 5:57

Fig. 4. Evacuation Time Record Chart

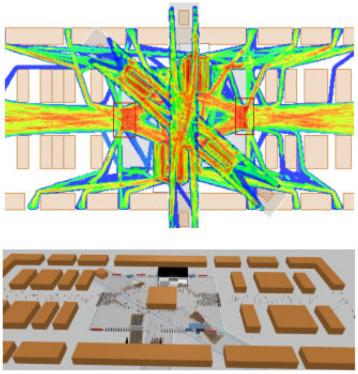


Fig. 5. Density map and heat map when the number of gates is 9

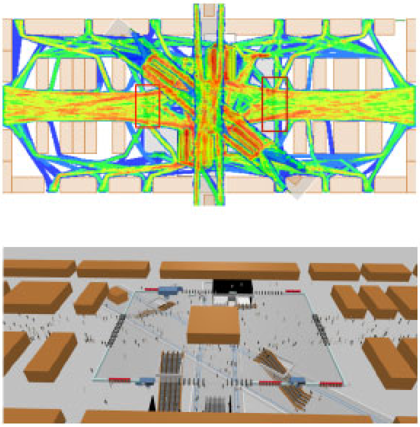


Fig. 6. Density map and heat map when the number of gates is 12

3.4 Simulation Results for Different Numbers of Gates

For each gate quantity plan, 100 simulations were conducted respectively, and the evacuation time for each simulation was recorded, 100 simulations were conducted for different numbers of gates, and the measured evacuation times were averaged to obtain $T_{\text{simulated}}$, which represents the actual simulated evacuation time. The final average evacuation times for each group are shown in Table 3.

Table 3. The actual simulation evacuation time with different numbers of gates

Number of gates	9	10	11	12	13
Evacuation time	350.74	336.01	326.82	317.94	314.80

Based on the calculation results of theoretical evacuation time and actual simulation evacuation time, the relative error between the theoretical estimation and the simulation simulation of evacuation time was further obtained (as shown in Table 4). The calculation formula for the relative error is:

$$\delta = \frac{\left|T_{theoretical} - T_{simulated}\right|}{T_{simulated}} \times 100\% \tag{7}$$

Table 4. Comparison of theoretical and actual evacuation times with different numbers of turnstiles

c	W_s	$T_{\text{theoretical}}$	$T_{\text{simulation}}$	δ
9	Inf	Inf	350.74	Inf
10	14.94	320.62	336.01	4.58%

11	4.83	310.51	326.82	4.99%
12	3.39	309.07	317.94	2.79%
13	3.11	308.79	314.80	1.91%

By comparing the evacuation time calculated through theoretical calculations with the actual simulation evacuation time (Figure 7), it can be seen that as the number of gates increases, the total time predicted by the theoretical model and the evacuation time of the simulation model show a consistent downward trend, and the rate of decline gradually slows down. This verifies the effectiveness of the queuing theory model in predicting the trend of evacuation efficiency changes.

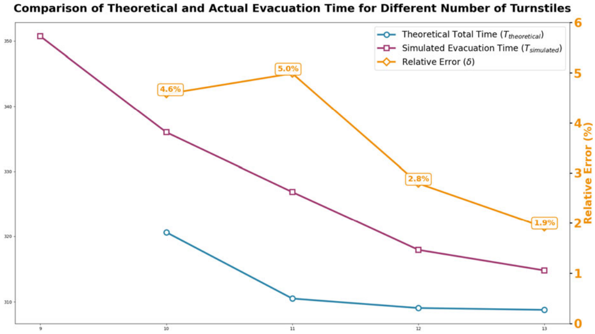


Fig. 7. Comparison curve of theoretical calculation and simulation evacuation time

4 Conclusion

This research can provide a reference for the emergency renovation and new configuration of railway hubs. However, this article mainly focuses on the design based on peak-hour passenger flow data. This renovation plan has good benefits in cases of heavy passenger flow, but it only causes congestion during certain specific times throughout the year. Therefore, based on the algorithm's calculation of the optimal number of gates, the station facilities can be actively renovated. Then, during daily operations, the added gates can be closed, and they can be opened for use during special peak hours. If the number of people is too large, station service staff can be arranged to provide route guidance. In subsequent research, a more detailed pedestrian behavior model can be introduced to enhance its universality.

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