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Research on Passenger Flow Control Plans for a Metro Station based on Social Force Model

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ABSTRACT

To better utilise the service capacity of the limited facilities of a metro station, as well as ensure safety and transport efficiency during peak hours, a large passenger flow control plan is studied through theoretical analysis and numerical simulation. Firstly, by passenger data collection and data analysis, the characteristics of the inbound and outbound passenger flow of a T metro station are analysed. Secondly, AnyLogic evacuation simulation models for the T Station during peak hours, peak hours without/with passenger flow control are established based on real passenger flow data as well as the station structures and layouts by using the AnyLogic software. The results show that there are no obvious congestions in the station hall, and the travel delay is significantly reduced when effective passenger flow control measures are taken. By controlling the speed, direction and movement path of passengers, as well as adjusting the operation of escalators, entrances and automatic ticket-checking machines, passenger flow can become more orderly, transport efficiency can also be improved, and congestion in the station can be well mitigated.

KEYWORDS

urban rail transit; metro station; passenger flow; simulation; control plan.

1. INTRODUCTION

In recent years, the rapid development of urban metro systems in China has resulted in a significant increase in the number of passengers in metro stations [1, 2]. In many large cities in China, metro systems are the main transportation method for residents and tourists, usually carrying a significant proportion of public transport [3]. Due to limited dredging capacity, some metro stations gather a large number of people in the station during the morning and evening commute and peak passenger flows on holidays, which has a great impact on the safety, comfort and travel efficiency of passengers [4]. Passenger flow management and safety of metro stations have generally become an important issue that needs to be studied [5, 6].

Researchers from all over the world have conducted various research on the control methods of large passenger flow in metro systems. Xue et al. (2019) put forward passenger flow control plans with 3 levels, specifically the platform control plan, paid area control plan and entrance control plan. In these plans, controlled entry of inbound passengers will be implemented at the platform, ticket-checking machines and the entrances [7]. By obtaining the inbound, outbound and passenger flow of transfer stations in different periods, Weng et al. (2016) proposed an evaluation method for the saturation degree of passenger flow at key locations of transfer stations, as well as a classification method for the congestion risk [8]. By adopting the cluster analysis method, Tang (2018) analysed the time distribution characteristics of passenger flow in typical metro stations. In his method, the passenger flow data of peak hours and flat hours were taken into account [9]. Based on a real metro station in Beijing, Li et al. (2016) introduced some multi-layer measures to limit the passenger flow and the corresponding auxiliary measures to evacuate the crowd to provide a gauge in the event of large-scale activities to ensure safety [10]. Tang et al. (2012) analysed the classification and characteristics of large passenger flow and gave a detailed analysis of organisation principles and methods for urban rail transit stations under large passenger flows [11]. Jiang et al. (2018) proposed an optimisation algorithm for coordinated passenger inflow dynamic control based on reinforcement learning to minimise station safety risk [12]. Based on the system control theory, Zeng et al. (2018) transformed the metro network passenger flow distribution into a system state equation, established a metro network-level passenger flow control decision model, and realised optimal control of network stations [13]. Feng S. et al. (2019) and Yang A. et al. (2018) proposed a coordinated flow-control optimisation model for unexpectedly large passenger flows. Based on an analysis of the passenger OD dataset (a dataset that includes passengers' origins and destinations) and relevant parameters of various metros, they built a mathematical model with the constraints of passenger flow demand, inter-regional transportation capacity, platform safety and so on. Their goal was to minimise average waiting time and maximise train carrying capacity. The model reduces the issue to a multiple linear regression problem. However, it needs a lot of data support, which brings more difficulties [14, 15].

As can be seen from the current research, there are many researchers focused on the coordinated control method model for large passenger flow in metro lines. However, there are few reports about the strategy and method for controlling large passenger flows at the station level. The current research is mainly based on the experience of metro station staff, lacking theoretical numerical verification and systematic and detailed passenger flow control plans. Based on a survey of the current situation of large passenger flows in typical metro stations in Guangzhou, China, this article has established simulation models of large passenger flow based on the social force model using AnyLogic software. Based on the analysis of the simulation results, a refined and optimised passenger flow control plan has been put forward, to provide a reference for passenger flow management of similar metro stations.

2. SOCIAL FORCE MODEL AND ANYLOGIC

2.1 Social force model

The social force model is very common in crowd evacuation research. It was proposed by Helbing and Molnar in 1998 according to the hydrodynamic equation. According to the social force model, the pedestrian is driven by three forces: the self-driving force which makes the pedestrian move toward the destination, the interaction force between pedestrians and the interaction between pedestrians and the environment. The social force model is widely used because it can explain the phenomenon of self-organisation of pedestrians, the behaviour and psychological characteristics of pedestrians are consistent with the actual situation, and it can describe the interaction between pedestrians, as well as the environment and pedestrians [16, 17].

In the simple social force model, the mathematical expression of the social force on each pedestrian i is *Equation 1*:

$$m_i \frac{dv_i(t)}{dt} = f_i^0 \sum_{j(\neq i)} f_{ij} + \sum_w f_{iw} \tag{1}$$

in which, m_i, v_i, f_i^0 respectively represent the mass, speed and self-driving force of pedestrian i; f_{ij} represents the force exerted by pedestrian i by nearby pedestrian j; f_{iw} represents the force exerted by pedestrian i by nearby obstacle w.

2.2 Principle and steps of AnyLogic pedestrian traffic simulation

AnyLogic is a widely used modelling and simulation tool for discrete, system dynamics, multi-agent and hybrid systems. The pedestrian traffic simulation module of AnyLogic is developed based on the social force model, and the simulation modelling of pedestrian flow is realised based on the pedestrian library, which includes a spatial sign module, pedestrian movement module and so on [18].

When AnyLogic is used for the simulation of passenger flow in a metro station, the main steps include data collection, environment modelling, passenger behaviour modelling, 3D modelling, simulation display and result output. The process of AnyLogic simulation modelling for the passenger flow in a metro station is shown in *Figure 1*.

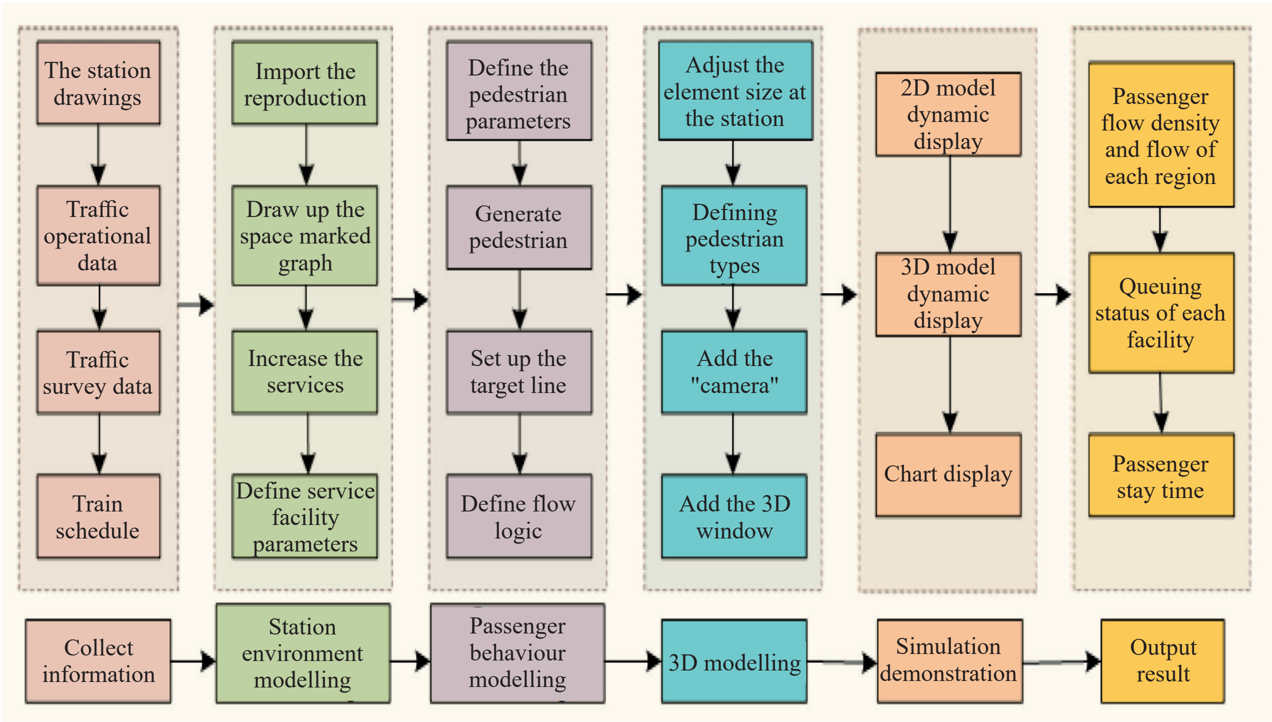

Figure 1 – The simulation modelling process of passenger flow in a metro station by AnyLogic

Data collection is a basic and necessary work in the process of model establishment. Data need to collect include the station structure, the layout of facilities, the passenger flow data, the characteristics of passengers, the train schedule, parameters of service facilities and equipment etc. The main steps of environment modelling include importing the station floor plan and the facility layout, drawing the space, setting the parameters of the service facilities, adding the target lines at the entrance and exit of the station or the escalators etc. Passenger behaviour modelling is realised by designing a pedestrian logic diagram with the help of *pedSource* (pedestrians generation), *pedService* (pedestrians receiving service), *pedEscalator* (pedestrians go up or down by escalator), *pedSelectOutput* (pedestrians destination selection), *pedGoTo* (pedestrians go-to destinations), *pedSink* (pedestrians disappear) [19]. 3D modelling is realised by creating 3D pedestrian types and adding cameras and 3D windows. The output results of the model include passenger flow density, passenger flow in each region, passenger queuing at each facility and passenger residence time.

3. PASSENGER FLOW ANALYSIS FOR T STATION

3.1 Information about T Station

Guangzhou is a city in southern China whose metro system went into operation in 1997 [20]. Its yearly passenger flow increase rate has been about 10% in the past decade, and the average daily passenger volume in 2018 reached 8 million, even exceeding 10 million on some holidays [21]. In recent years, the T Station of Guangzhou Metro has consistently ranked first in daily passenger flow in China. Here, by data collection from automatic ticket checking machines, the passenger flow characteristics and control plan of larger passenger flow during peak hours of T Station will be analysed and studied at first, and the passenger flow simulation model will also be established based on these data.

T Station is the interchange station of Line 1, Line 3 and Line 3A of Guangzhou Metro. The general station hall layout of T Station is shown in *Figure 2*. The station hall of Line 1 is in the north-south direction, while the station hall of Line 3 and Line 3A is in the west-east direction. The station hall of Line 1 has entrances/exits A, B, C and D, and the station hall of Line 3 and Line 3A has entrances/exits E, G and H. In *Figure 2*, S means escalators or stairways, and O/I means outbound/inbound automatic ticket-checking machine.

3.2 Passenger flow characteristics

The inbound, outbound and transfer passenger flows of T Station on typical working days and holidays are shown in *Figures 3 and 4*. It shows that the proportion of transfer passenger flow in T Station is basically between

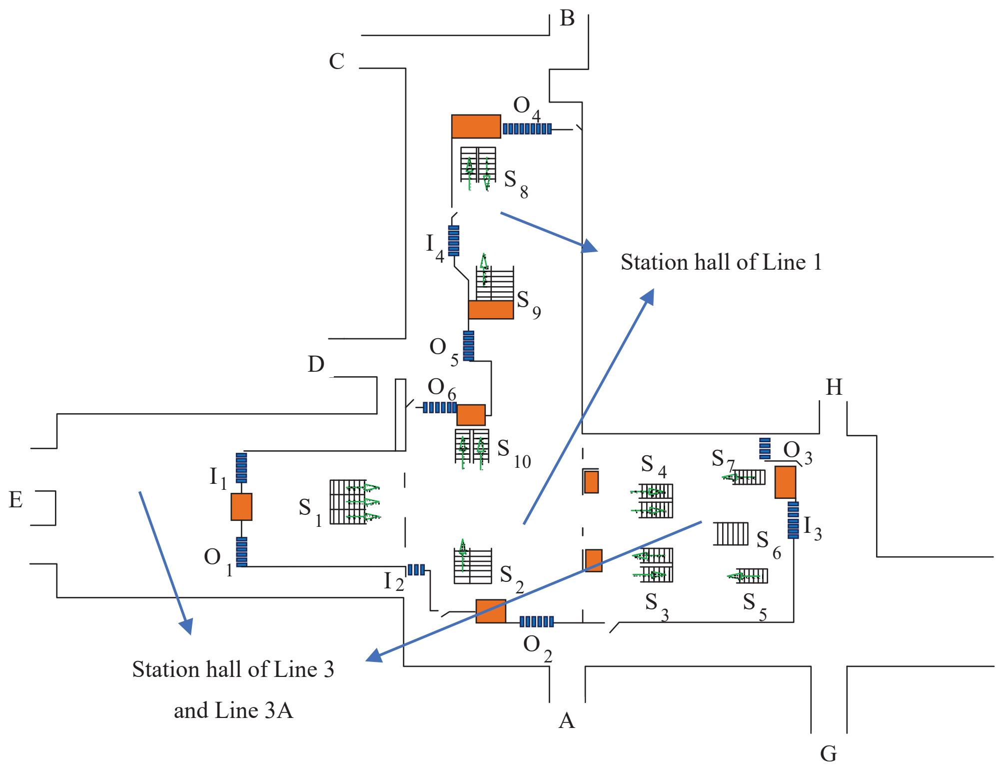

Figure 2 – The layout of the station hall of T Metro Station

55% and 80%, whether on working days or holidays. The passenger flow on a working day shows obvious tidal characteristics, the morning and evening peak passenger volume accounts for 40% of the total passenger flow. The morning peak of the working day occurs during 8:00–10:00, and the passenger flow mainly includes outbound and transfer passengers. While the evening peak of the working day occurs during 18:00–20:00, the passengers are mainly those transferring between different lines. The peak hour of the International Workers' Day is from 14:00 to 19:00, lasting for 5 hours, and the total number of passengers reached 325,000 on this day.

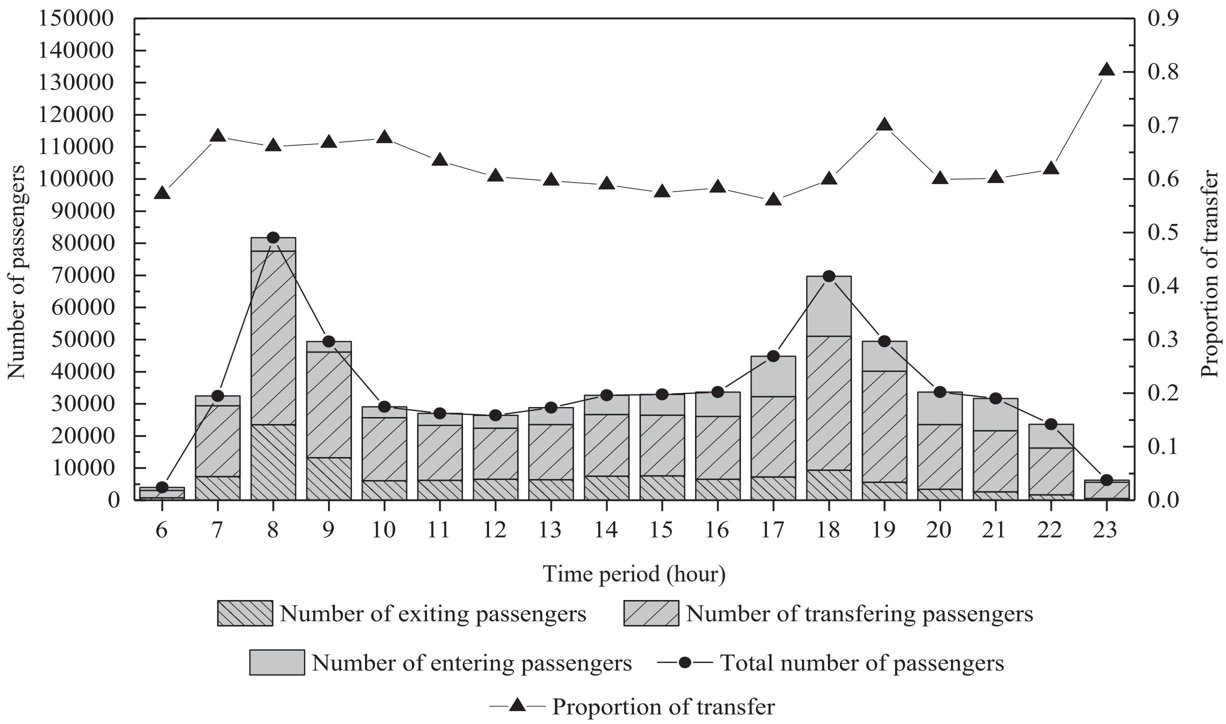

Figure 3 – Passenger flow distribution on a working day

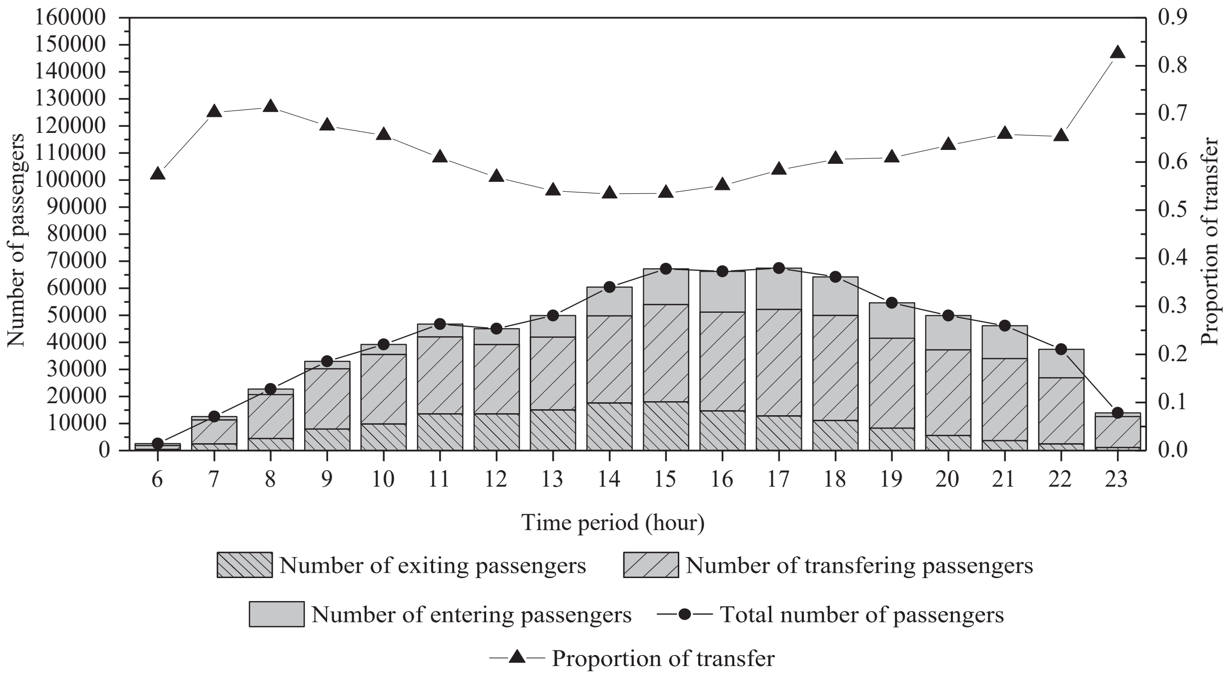

Figure 4 – Passenger flow distribution of a holiday (International Workers' Day)

3.3 Current passenger flow control plan

The current passenger flow control plan of T Station is divided into three levels according to the passenger flow intensity in the station. They are platform passenger flow control (Level 1), paid area of station hall passenger flow control (Level 2) and unpaid area of station hall passenger flow control (Level 3), as shown in *Figure 5*.

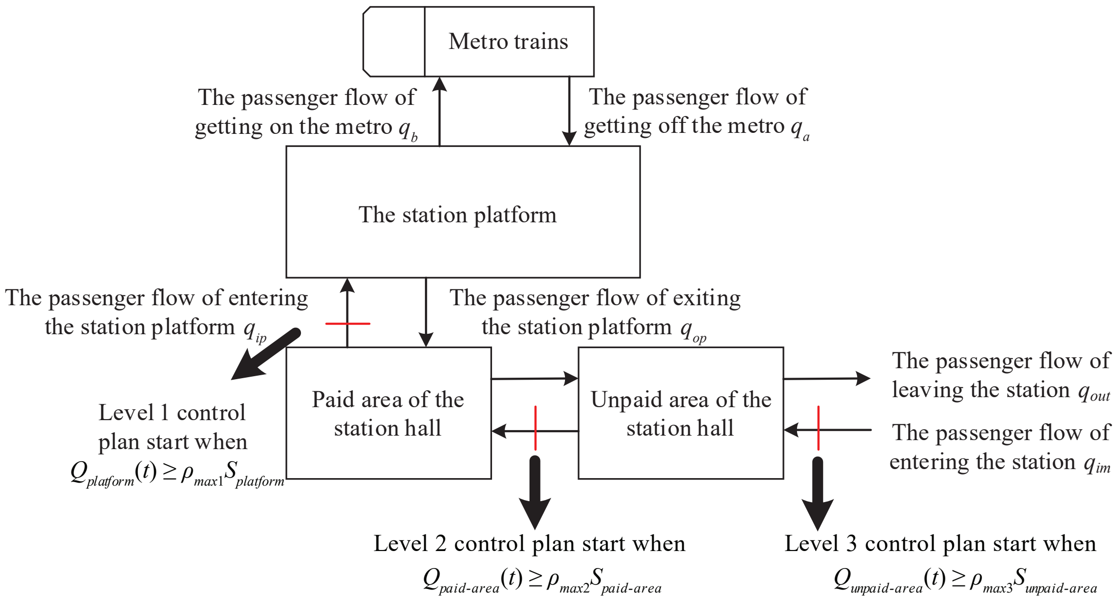

Figure 5 – The three-level passenger flow control plans of T Station

The key to the station-level passenger control plan is to determine the starting conditions, passenger flow restriction intensity and specific passenger control measures. When the passenger flow on the platform meets *Equation 2* or the queuing passengers arrive at the warning line, the Level 1 passenger flow control plan will be started. The main measures of the Level 1 control plan include installing iron fences at the stairs and escalators leading to the platform and diverting some escalators.

$$Q_{platform}(t) \geq \rho_{max1} S_{platform} \tag{2}$$

where $Q_{platform}(t)$ is the passenger flow on the platform; $S_{platform}$ is the effective area of the platform; ρ_{max1} is the maximum allowable passenger density on the platform.

After the Level 1 passenger flow control plan is started, the passenger number in the paid area of the station hall will increase. When the platform passenger flow meets *Equation 3* or the queuing passengers reaches the warning line of the paid area in the station hall, the Level 2 control plan will be started to avoid overcrowding. The measures include closing or adjusting some inbound gates to outbound gates, intercepting transfer passenger flow in the station hall, setting loop lines in the payment area etc.

$$Q_{paid\text{-}area}(t) \geq \rho_{max2} S_{paid\text{-}area} \tag{3}$$

where $Q_{paid\text{-}area}(t)$ is the passenger flow in the paid area of the station hall; $S_{paid\text{-}area}$ is the effective area of the paid area of the station hall; ρ_{max2} is the maximum allowable passenger density in the paid area of the station hall.

The passenger number in the station hall may continue to increase after the Level 2 control plan is started. When the passenger flow in the unpaid area meets *Equation 4* or the passengers are queuing up to the warning line of the un-paid area, the Level 3 control plan will be started. Control measures include closing some entrances of the station, shutting down some ticket vending machines and automatic ticket checking machines, shortening the trains' arrival intervals through traffic scheduling etc.

$$Q_{unpaid\text{-}area}(t) \geq \rho_{max3} S_{unpaid\text{-}area} \tag{4}$$

where $Q_{unpaid\text{-}area}(t)$ is the passenger flow in the unpaid area of the station hall; $S_{unpaid\text{-}area}$ is the effective area of the unpaid area of the station hall; ρ_{max3} is the maximum allowable passenger density in the unpaid area of the station hall.

Generally, the staff in the control centre of a metro station can estimate the crowd density of each area of the station according to their experience by observing the monitoring images, and the station staff (security, train-taking guide etc.) in the station hall and on the platform can also conduct on-site crowd density surveys. By these two methods, crowd densities in different areas of metro stations are obtained and then can be compared with the maximum allowable passenger densities.

3.4 Principles of passenger flow organisation

When passengers enter a metro station, most of them will automatically select a path with the shortest distance and lowest passenger flow density to the platform. The complexity of the passenger flow is affected by the station structure, the layout of service facilities and the demand of passengers during different periods. The organisation of passenger flow should be as simple and orderly as possible and avoid the intersection of

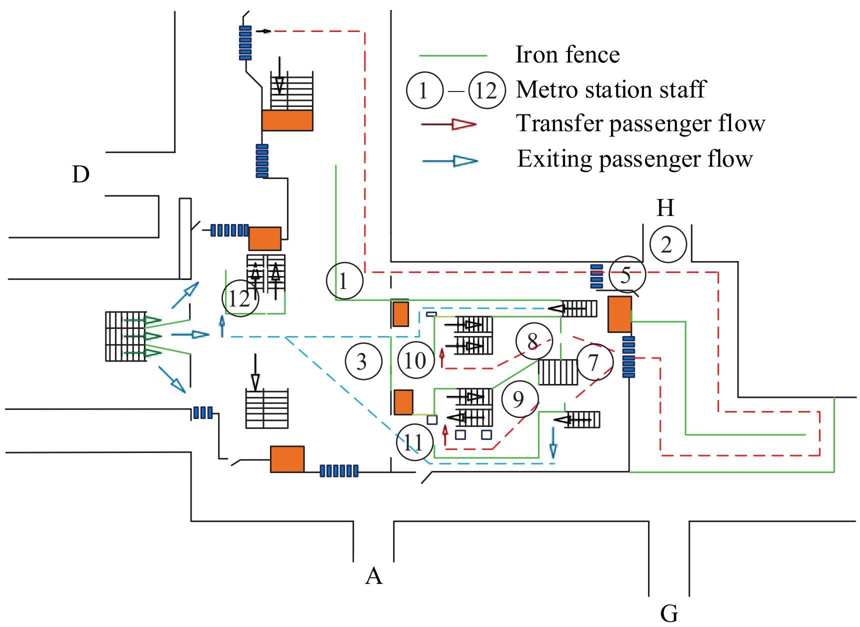

Figure 6 – Organisation diagram of Level-3 passenger flow control flow line

passenger flows. The passenger flow organisation adjustment should also take the structure and layout of the station into consideration, to make full use of the station space. In addition, intersections of passenger flows should be avoided.

Different levels of passenger flow control plans correspond to different passenger flow organisations. The passenger flow organisation of the three-level passenger flow control plan of T Station is shown in *Figure 6*. In case of a large passenger flow, passengers can be guided to detour reasonably by adjusting the direction of escalators and automatic ticket checking machines, setting iron fences and providing guidance by station staff or signs at important locations, to relieve the pressure of congestion in the station.

4. PASSENGER FLOW SIMULATION OF T STATION

4.1 Simulation design and basic assumptions

The actual passenger flow data of T Station during flat hours (11:00–12:00) and peak hours (17:00–18:00) on a typical super-large passenger flow day (28 April 2018) is selected to be the basic input data of the simulation model. These different conditions will be simulated, they are flat peak hours, peak hours without passenger flow control and peak hours with passenger flow control. A comparative analysis of congestion in the station and the delay of passengers in the three conditions will be carried out based on the simulation results.

The simulations mainly focus on the impact of station structure, facilities layout and control measures on passenger flow. Therefore, the following reasonable simplifications will be made when establishing the models:

a) The passenger flow is generated at a uniform speed at *pedSource*. This is done due to the limitations in the functionality of the simulation software, while the total number of passengers in different passenger flow directions will keep consistent with the statistical results of the real situation.
b) Assuming that all passengers who enter T Station hold an e-ticket or metro card, taking the metro by metro card or via mobile payment has already become very common in Guangzhou, as only some among the older population or travellers will buy tickets from the ticket vending machines.
c) Assuming that all passengers will use escalators or stairways to leave or go to the platform. The elevators in the station hall are for people with mobility impairments, and most passengers will use escalators or stairways to get to the platform.
d) The influence of the column in the station hall and on the platform is ignored. This is because the columns are located in the central part of the station hall, while the passengers' walk routes are on the sides of the station hall.

4.2 Basic parameters of models

The passenger flow data of each flow direction in the station hall of T Station is shown in *Table 1*, and these data were obtained by exporting the passenger data from automatic ticket checking machines at every entrance. The proportion of inbound passengers at each entrance is shown in *Table 2* and the proportion listed in *Table 2* is determined based on assumptions according to the suggestions of staff at T Station. The passengers moving from the platform to the station hall include transfer passengers and outbound passengers, and they will use elevators and escalators evenly.

The initial moving speed is set to meet the random distribution of (0.3, 0.7) m/s, the comfortable speed in the passenger station is set to meet the random distribution of (0.5, 1.3) m/s, and the body diameter of passengers is set to meet the random distribution of (0.4, 0.5) m.

Before passengers can get on the train, they will need to take the security check, go through the automatic ticket-checking machines and use the escalator or stairways. According to the metro design specification, the service capability of the security inspection machine is 1200 persons/h. The service capability of the automatic ticket-checking machines is 1800 persons/h in one direction. The escalators are 1 m wide, with a moving speed of 0.5 m/s, and their service capacities are 6720 persons/h. There are 6 stairways in total; among them, S_6 is a downward stairway with a service capacity of 4200 persons/h, and S_2 and S_9 are both up-down mixed stairways with a service capacity of 3200 persons/h, S_1 (central part) is an upward stairway with a service capacity of 3700 persons/h.

Table 1 – Passenger flow of station hall in flat and peak hours (persons)

Period / Passenger flow directions	Flat hours	Peak hours
Inbound passenger flow of Line 1	1,731	4801
Inbound passenger flow of Line 3	3,035	9239
Outbound passenger flow of Line 1	2,501	3,697
Transfer from Line 1 to Line 3	4,933	8,690
Outbound passenger flow of Line 3	5,114	6,795
Transfer from Line 3 to Line 1	4,910	8,430

Table 2 – Number of passengers entering from each entrance and control measures (persons)

The proportions of passenger flow at each entrance	Flat hours	Peak hours without passenger control	Peak hours with passenger control
A（14%）	667	1,965	1,965
B（7%）	334	983	983
C（10%）	477	1,404	1,404
D（10%）	477	1,404	1,404
E（25%）	1192	3,510	3,510
G（16%）	762	2,246	2,246
H（18%）	858	2,527	2,527

Before passengers can get on the train, they will need to take the security check, go through the automatic ticket-checking machines and use the escalator or stairways. According to the metro design specification, the service capability of the security inspection machine is 1200 persons/h. The service capability of the automatic ticket-checking machines is 1800 persons/h in one direction. The escalators are 1 m wide, with a moving speed of 0.5 m/s, and their service capacities are 6720 persons/h. There are 6 stairways in total; among them, S_6 is a downward stairway with a service capacity of 4200 persons/h, and S_2 and S_9 are both up-down mixed stairways with a service capacity of 3200 persons/h, S_1 (central part) is an upward stairway with a service capacity of 3700 persons/h.

4.3 Passenger flow control measures

For the condition "peak hours with passenger flow control", Level-3 passenger control measures will be started. The measures in detail are listed below:

a) Adjust the direction of the escalators. The direction of S_2 and S_8 is diverted from downward to upward, while S_3 is diverted from upward to downward. S_6 is closed.

b) Some entrances/exits will close or adjust to enter only or exit only. Entrance E is closed, H and A is switched to enter only, while G is switched to exit only.

c) Automatic ticket-checking machines O_3, I_3, O_2, O_6, O_5, and I_4 are switched to remain open, while O_1 and I_2 will close.

d) Passenger flow organisation. To avoid congestion, the routes of passengers are reorganised. Measures including adjust the transfer route between Line 1 and Line 3, inbound passenger flows of Line 1 and Lind 3A to make them detour. Besides, Guide the outbound passengers exit the station via the designated ticket-checking machine.

e) Guidance of station staff. Arrange station staff to stand at the key control locations, such as escalators to guide passengers. Passengers who enter from B and C will be guided to enter the paid area through I_4, passengers who enter from A and D will be guided to enter through I_1, and passengers who enter from H will be guided to enter through I_3.

f) Control the speed of passengers entering T Station. The basic principle of passenger flow control is first-out and then-in. Through the simulation experiment, the optimal number of entering passengers at each entrance is 600 per hour.

4.4 Analysis of simulation results

Figures 7–9 show the crowd density in the station hall during the flat hours, peak hours without passenger flow control, and peak hours with passenger flow control, respectively. It can be seen from *Figure 7* that the crowd density in the station hall during flat hours is generally low due to small passenger flow, and no serious congestion is observed in the station hall.

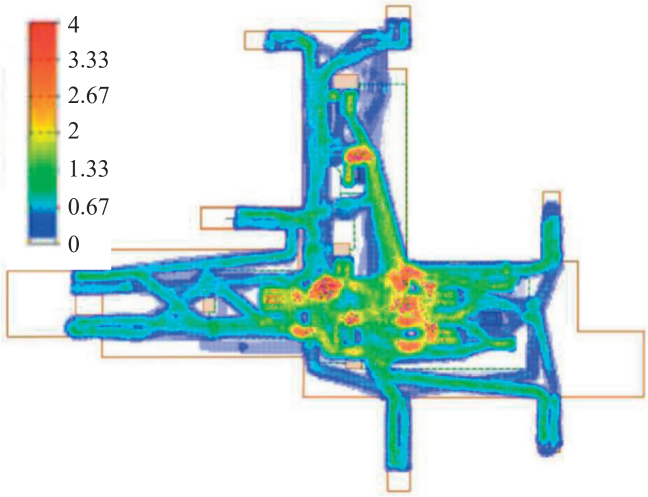

Figure 7 – Crowd density during flat hours (persons/m^2)

As can be seen from *Figure 8*, serious congestion can be observed during peak hours when passenger flow control measures are not adopted. Serious congestion can be found in the intersection area of Line 1 station hall and Line 3, Line 3A station hall, as well as some entrances. The maximum crowd density of these areas is about 4 persons/m^2.

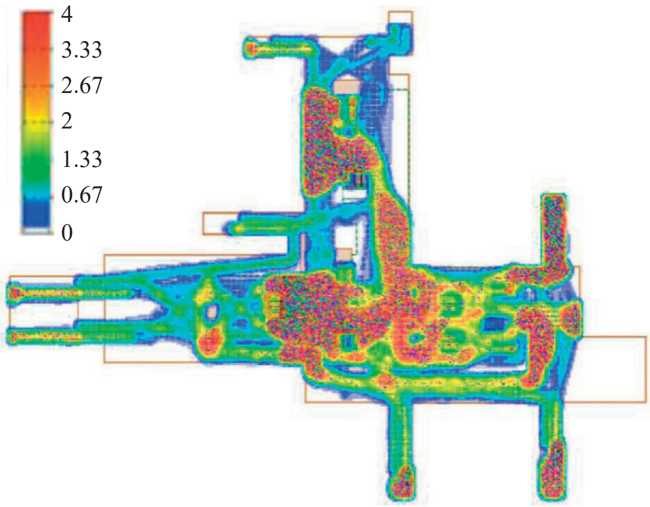

Figure 8 – Crowd density during peak hours without passenger flow control (persons/m^2)

By comparing *Figure 9* with *Figure 8*, it can be found that the crowd density in the station hall is greatly reduced after control measures for mass passenger flow are adopted. The serious congestion found in *Figure 8* no longer occurs, which shows the passenger flow control measures are effective.

The comparison of the crowd density and passengers' travel time simulation results under different conditions is shown in *Figure 10* and *Figure 11*. The relevant research report classifies the crowd density and comfort level of the station, pointing out that when the average crowd density of the metro station exceeds 1.74 persons/m^2, passengers will be in an uncomfortable and dangerous state [22]. Therefore, 1.74 persons/m^2 is selected as the maximum allowable safety crowd density for the following analysis.

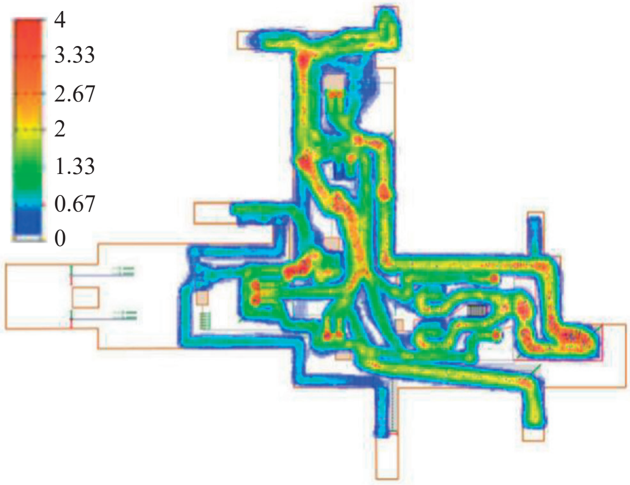

Figure 9 – Crowd density during peak hours with passenger flow control (persons/m²)

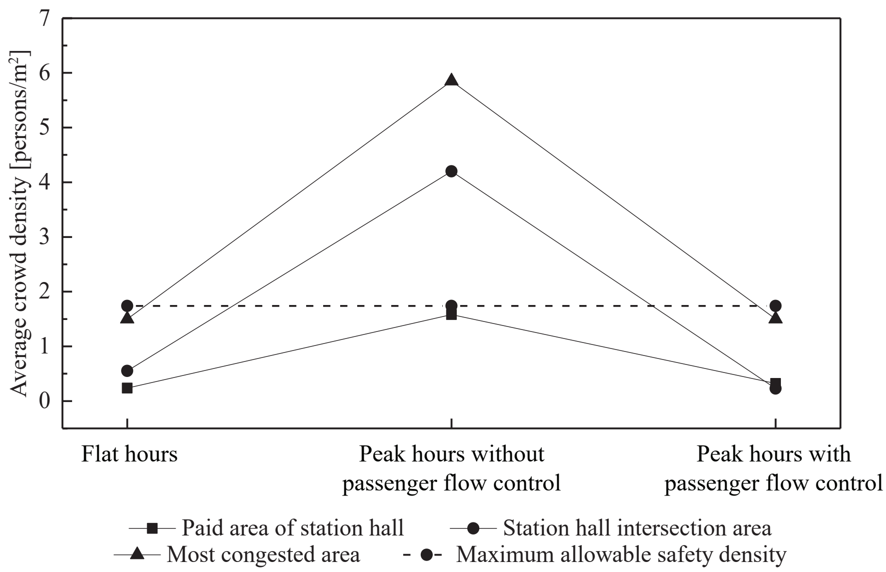

Figure 10 – Comparison of the simulation results of average crowd density

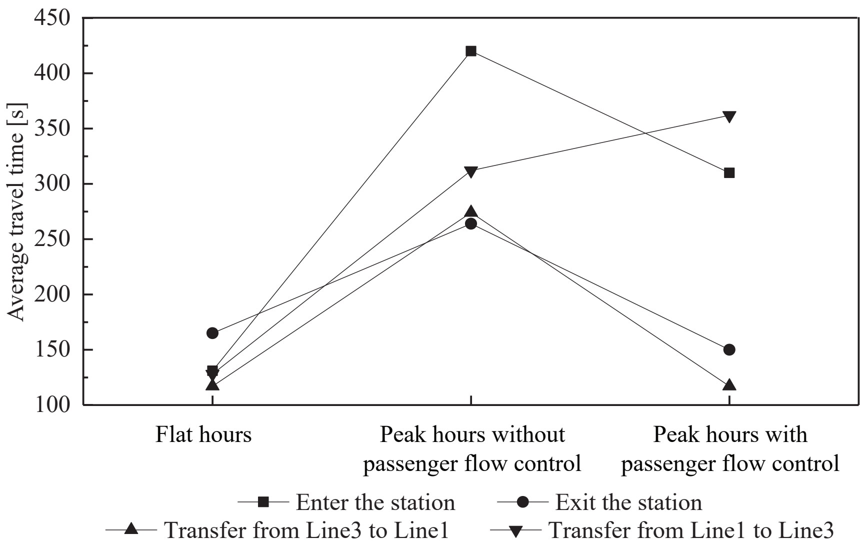

Figure 11 – Comparison of the passengers' average travel time

According to *Figure 10*, in case of a peak passenger flow in the station, the average crowd density in the station hall will increase rapidly if no effective passenger flow control measures are adopted. The average crowd density in the paid area of the station hall will reach 1.58 persons/m^2, the crowd density in the intersection area of Line 1 station hall, and Line 3, Line 3A station hall will reach 4.2 persons/m^2, while the crowd density in the most congested area will reach 5.8 persons/m^2. In short, the passenger flow density in many areas of the station hall will exceed the maximum allowable safety density if no control measures are taken. When the passenger flow control measures are adopted, the average crowd density in the paid area of the station hall will reduce to about 0.32 persons/m^2, and the crowd density in the most congested area will reduce to about 1.5 persons/m^2. In general, the crowd density in the station hall will reach a safe state when passenger flow control measures are adopted.

In terms of travel time, in case of peak passenger flow in the station, the average time needed for passengers to enter the station will increase by 289 s compared with the flat hours. Also, the average time needed to exit will increase by 99 s, and the average transfer time from Line 1 to Line 3 and Line 3 to Line 1 will increase by 184 s and 157 s, respectively.

After the passenger flow control measures are adopted, the average time needed for passengers to enter the station is 179 s, which is 110 s less than that in peak hours without control. The average time needed to exit will reduce to 150 s, which is even less than the time needed during flat hours. The average transfer time from Line 3 to Line 1 is the same as in the flat hours, while the passengers transferring from Line 1 to Line 3 need to detour in the station hall due to the influence of passenger flow organisation. Thus, the transfer time will become 50 seconds longer than when no control measures are taken.

5. CONCLUSIONS AND FUTURE WORKS

By theoretical analysis and numerical simulation, the effectiveness of a station-level large passenger flow control plan has been studied. AnyLogic models based on the T Station of Guangzhou Metro are established, and the simulation results of flat peak hours, peak hours without passenger flow control, and peak hours with passenger flow control have been compared. The main conclusions listed below can be achieved:

1) Through data collection and field research, the characteristics of passenger flow and control plan for the T Station, a typical crowd metro station are analysed and studied. The key to the platform, paid and unpaid area passenger flow control plans is to determine the starting conditions, passenger flow restriction intensity and specific passenger control measures.
2) Social force models based on T Station have been established, and three different conditions of T Station were simulated, specifically flat peak hours, peak hours without passenger flow control and peak hours with passenger flow control. The simulation results show when effective passenger flow control measures are taken, the average entry time, exit time, and the time delay of transfer from Line 3 to Line 1 are reduced by 110 s, 114 s and 157s, respectively, compared to when passenger control is not adopted. This indicates that by controlling the speed, direction and movement path of passengers, as well as adjusting the operation of escalators, entrances and automatic ticket-checking machines, passenger flow can become orderly, travel efficiency can be improved, and congestion in the station can be mitigated as well. This improves the safety of passengers while saving their time.

In the following research, the operation of metro trains can be combined with the simulation models to further study how to improve passenger flow management by optimising the train schedules. Also, the proposed method will be applied to metro stations with different structures and layouts in further studies.

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基于社会力模型的地铁车站客流控制方案研究

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摘要：
为了更好地利用地铁车站有限设施的服务能力，保证高峰时段的安全和运输效率，通过理论分析和数值模拟研究了大型客流控制方案。首先，通过乘客数据采集和数据分析，分析了地铁T站进出站客流的特点。其次，利用AnyLogic软件，根据实际客流数据，结合车站结构和布局，建立T站高峰时段、无客流控制时段和有客流控制时段的疏散仿真模型。计算分析结果表明，采取有效的客流控制措施后，车站大厅内没有出现明显的拥堵现象，出行延误明显减少。通过控制乘客的速度、方向和移动路径，以及调整自动扶梯、出入口和自动检票机的运行，可以使客流更加有序，提高运输效率，很好地缓解地铁车站的拥堵。

关键字：
城市轨道交通；地铁车站；客流；模拟；控制方案