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Passenger Queuing Analysis Method of Security Inspection and Ticket-Checking Area without Archway Metal Detector in Metro Stations

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ABSTRACT

In order to avoid the congestion in front of the entrance gate units, it is necessary to analyse and optimise the queuing situation at the planning and design stage. The security inspection area and the ticket-checking area were jointly considered, and a queuing congestion analysis method was proposed. Firstly, the research problem was stated. Then, the problem of calculating the number of passengers in each subarea at any time was transformed into the problem of calculating the transit time of each passenger in each subarea. The transit time was divided into basic transit time and additional transit time. Based on the velocity-density relationship, a quantisation method for basic transit time was proposed related to passenger arrival time. The additional transit time was determined by the moment when the passengers left the subarea according to the sequence of arrival of passengers, the number of queuing passengers in the subarea and the congestion of the subarea to be entered. Finally, the queuing situation of passengers in each subarea at any moment was obtained through passenger flow recursion. Examples showed that the proposed method can deal with multiple working conditions and avoid the tedious and time-consuming scene construction process of the microsimulation software.

KEYWORDS

metro station; security inspection area; ticket-checking area; passenger queuing; transit time; passenger flow recursion.

1. INTRODUCTION

Metro transit is playing an important role in the urban transportation system [1]. The transit station is a key component of the metro transit network. The non-payment area has become a capacity bottleneck of the station. It is common to see long queues of passengers passing through the automatic fare gates in the non-payment area (i.e. area where passengers buy tickets or get proof of payment before entering the paid area at a transit station) [2]. In order to prevent the front of the entrance gate unit of the metro transit station from being too congested, the scheme should be optimised and adjusted in the planning and design stage.

Current congestion analysis methods for the front of the entrance gate unit can be classified into two categories: microscopic simulation method and queue theory method.

Many researchers use pedestrian flow micro-simulation tools to simulate the pedestrian movements in the rail transit station [3] and obtain the results, including traffic time, pedestrian density, speed, volume and level of service [4]. These results can be used to evaluate the congestion level of pedestrian facilities in the station.

Hoogendoorn et al. used the microscopic simulation model NOMAD and examined the effects of installing entry and exit gates in stations in the Lisbon metropolitan area [5]. Zhao et al. tested the pedestrian traffic organisation plans of DONGSISHITIAO subway station of line 2 in Beijing involved during the Olympics using the Legion 2006 studio [6]. Lei et al. conducted a simulation of the process of pedestrian crowds' evacuation from a huge transit terminal subway station using FDS + Evac simulation software [7]. King et al. developed, calibrated and validated a model of the station in the pedestrian simulator MassMotion software, which was used to analyse crowd congestion and mitigation at Bloor-Yonge Station, Toronto, Ontario [8]. Yang et al. took Hangzhou Wulin Square Station of Metro Line 1 for example and dynamically optimised the opening number of the entrance ticket gates at the station based on AnyLogic [9]. Liao and Liu used microscopic simulation models to investigate passenger behaviour in the non-payment area with the cellular automata (CA) model [1]. Hoy et al. were involved in the development of a set of high-fidelity pedestrian microsimulation models that were used to plan the improvement of a major intermodal hub with MassMotion software [10]. Chen et al. proposed a multiagent-based subway station simulation model [11]. Ni et al. used AnyLogic simulation software to establish a station simulation model for Youfangqiao Station of Nanjing Metro Line 2 [12]. Zhu simulated and analysed the passenger flow of Xiamafang metro station with the help of the traffic behaviour model theory of pedestrians by using AnyLogic [13]. Kim and Kim ran an agent-based simulation to calculate the frequency of the agent movement at each gate, which is matched with the observed pedestrian volume, using pedestrian data from Gangnam Station [14]. Lin et al. studied the effects of gate machines on crowd traffic based on simulations using the modified social force model [15]. Yamada and Utaka constructed an agent-based model to simulate the movement of flowing people through the train station concourse according to the time of day, number of stationary people present and ticket gate directional restrictions [16]. According to reference [17], in addition to the simulation software mentioned in the above works of literature, simulation software in common use includes VisWalk, SimWalk Transport, etc.

When using the micro-pedestrian flow simulation tool to analyse the station congestion, users can easily observe the passenger flow queuing congestion at any position in the scene at any time, such as passenger flow density, queuing length, service level, etc. However, before the simulation, any simulation tool needs to build a simulation environment. Generally, CAD drawings or BIM models need to be imported into the software as the base map, and then the corresponding simulation environment is built according to the base map. This process consumes a lot of time and energy for the designers. Guo and Gu combined the actual case and explained that the actual time consumed to complete a simulation analysis with Legion software may exceed 14 hours [18]. Guo also summarised the input process, output process and operation process of the pedestrian flow simulation of Legion, Anylogic and VISSIM, respectively, and pointed out that if the pedestrian simulation software is used to implement the multiple modifications and evaluations of the scheme, this recurrent process will bring huge workload [19].

In fact, the tedious and time-consuming simulation scene construction process is one of the bottlenecks of the microsimulation method for the congestion diagnosis and optimisation of pedestrian facilities layout schemes in rail transit stations.

The queue theory method considers pedestrian facilities as a queuing mode. Jiang and Luo abstracted the automatic fare gates and passengers into a queue system, utilised AnyLogic software to simulate the process of passengers getting through the automatic fare gates, and then established optimal experiments to search the best configuration of automatic fare gates in different conditions of passenger characteristics [20]. Xu et al. presented a methodology for modelling a single node (staircase, walkways, gate, hall, escalator) with unidirectional pedestrian flows as an M/G/C/C state-dependent or M/M/C/C queue [21]. Khattak et al. proposed a PH-based simulation-optimisation approach that fully considers the fluctuation, the state dependence, the level of service (LOS) and the blocking effect [22].

The queuing theory method can only output a few static indicators such as queue length and queue time. These static parameters cannot reflect the dynamic process of the security inspection and ticket-checking area in the passenger access/egress process, such as queue length at any moment.

In the above studies except for reference [13], the vast majority of researchers assumed that passengers do not need to go through security inspection. But, in China, passengers must undergo safety checks after entering urban rail transit stations. When the staff confirms that the passenger is not carrying dangerous goods, the passengers can walk to the entrance gate unit. Especially during the morning and evening rush hours, a large number of queuing passengers are generated at the ticket machine/manual service window and security check office (especially at the transfer station and the railway passenger transport hub junction station). After layers of weakening, the number of passengers detained at the access gates is small, resulting in small-scale queuing [23]. Liu et al. jointly considered the security inspection equipment and the automatic ticket gate and established an optimisation model of the queuing network construction system based on the combination of series and parallel [24]. Tang proposed the concept of a double-check system with further consideration of the linkage between the security check machine and the ticket gate, believing that the security check and the ticket gate have interrelated effects. Tang then established a queuing network model that divided passengers into passengers with bags and passengers without bags [25]. In summary, when analysing the queuing and congestion situation of the entrance gate unit, it needs to be considered jointly with the security check process, and it should be distinguished whether passengers carry bags.

In view of the above situation, this paper will propose a new passenger flow queuing analysis method for the security inspection and ticket-checking area of metro stations, which can not only avoid the tedious and time-consuming scene construction process of the microsimulation software but also reflect the dynamic changes of the whole process of passenger distribution.

2. METHODOLOGY

The security inspection and ticket-checking area in this paper is composed of an X-ray security inspection instrument, a gate unit and its surrounding area, as shown in *Figure 1*. The whole area can be divided into three parts, which are called subarea1, subarea2 and subarea3, respectively. In subarea2, one side near the X-ray security inspection instrument is occupied by passengers carrying items that need to be checked (called passengers1), which is called passageway1, while the other side is called passageway2, which is occupied by passengers carrying no items that need to be checked (called passengers2). The width of passageway1 is generally the width of a person. Some stations will add railings between the two passageways, so the width of passageway1 is the distance between the railings and the security detector.

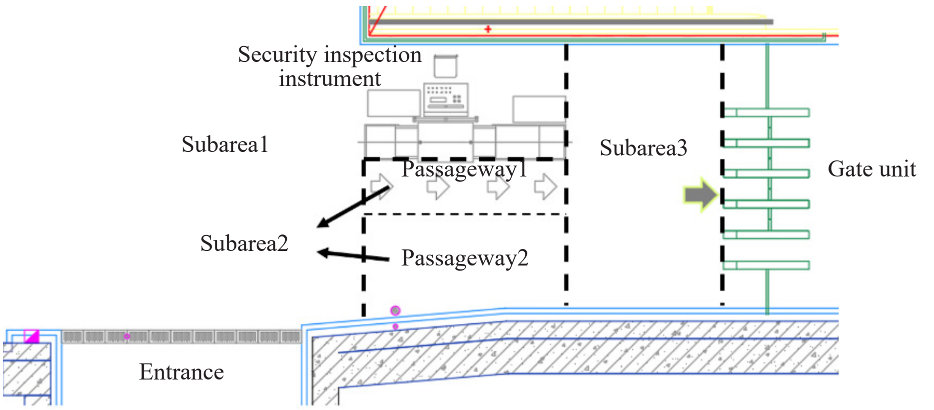


Figure 1 – A security inspection and ticket-checking area

The problem dealt with in this paper is to take the security inspection and ticket-checking area shown in *Figure 1* as an example to analyse the passenger queuing in all subareas in the passenger access/egress process.

For each security inspection and ticket-checking area, the passenger access/egress process can be regarded as the collection of the processes of each passenger from departing the entrance to leaving the gate unit. The passengers enter the station hall floor from the entrances with an arbitrary distribution over a certain period of time, and the passengers finally enter the payment area through the gate unit. Passenger access/egress processes in security inspection and ticket-checking area of passengers1 and passengers2 are shown in *Figure 2*.

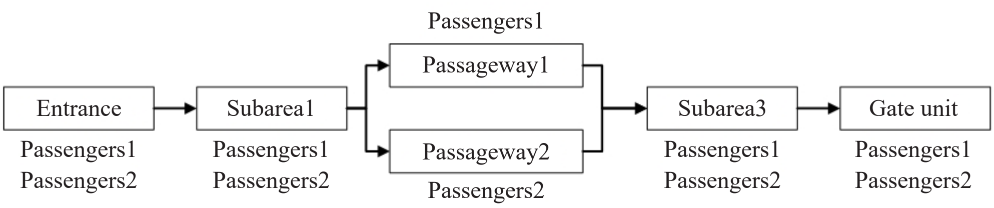


Figure 2 – Passenger access/egress process in security inspection and ticket-checking area

If the time spent by each passenger passing through each subarea can be obtained, and the statistics of each subarea at any time can be made, the queuing situation of each subarea in the security inspection and ticket-checking area can be obtained in the passenger access/egress process. Therefore, it is necessary to determine the entry time and departure time of passengers in each subarea.

Assuming that the passenger arrival distribution at the entrance is known, that is, the entry time of any passenger in subarea1 is known, and because the departure time of a subarea is the entry time of the next subarea, the problem can be converted into calculating the transit time of passengers in each subarea. The transit time can be divided into the following two parts: (1) when passengers are about to enter a sub-area, assuming that passengers will not be disturbed when passing through the subarea, the basic transit time can be determined according to the velocity-density relationship of the subarea at the current time or the running speed of the equipment; (2) if passengers wait in line when passing through a subarea, the actual departure time should be added a period of time on the basis of the expected departure time, which can be called additional transit time. Therefore, the key of the method is to determine the basic transit time and additional transit time for each passenger in different subareas.

2.1 Quantitative method of basic transit time

Generally, subarea1 is an unclosed area with a relatively large area. Passengers can move forward at free-flow speed v_0 in this area. According to different destinations, the basic transit time of passengers1 and passengers2 in subarea1 are shown in *Equations 1 and 2*

$$t_{\mathrm{PA1,SA1}} = \frac{L_{\mathrm{EN,PW1}}}{v_0} \tag{1}$$

$$t_{\mathrm{PA2,SA1}} = \frac{L_{\mathrm{EN,PW2}}}{v_0} \tag{2}$$

where $t_{\mathrm{PA1,SA1}}$ is the basic transit time of passengers1 in subarea1; $t_{\mathrm{PA2,SA1}}$ is the basic transit time of passengers2 in subarea1; $L_{\mathrm{EN,PW1}}$ is the distance from the entrance to passageway1; $L_{\mathrm{EN,PW2}}$ is the distance from the entrance to passageway2.

As shown in *Equation 3*, the basic transit time of passengers1 in passageway1 can be divided into three parts: the time for placing items t_{pi}, the time for security inspection and the time for taking items t_{ti}. The time for security inspection depends on the transmission length and speed of the X-ray security inspection instrument;

$$t_{\mathrm{PA1,PW1}} = t_{pi} + \frac{L_{SE}}{v_{SE}} + t_{ti} \tag{3}$$

where $t_{\mathrm{PA1,PW1}}$ is the basic transit time of passengers1 in passageway1; L_{SE} is the length of the conveyor belt in the X-ray security inspection instrument; v_{SE} is the running speed of the X-ray security inspection instrument.

The passageway2 can generally be regarded as a horizontal passage. The basic transit time of passengers2 in this area can be determined according to the velocity at the time of entry, as shown in *Equation 4*

$$t_{\mathrm{PA2,PW2}} = \frac{L_{\mathrm{PW2}}}{v_{\mathrm{PW2}}\left(K_{\mathrm{PW2},T_{\mathrm{PW2},in}}\right)} \tag{4}$$

where $t_{\mathrm{PA2,PW2}}$ is the basic transit time of passengers2 in passageway2; L_{PW2} is the length of passageway2; $T_{\mathrm{PA2},in}$ is the time when passengers2 enter the passageway2. $K_{\mathrm{PW2},T_{\mathrm{PA2},in}}$ is the passenger density of the passageway2 at $T_{\mathrm{PA2},in}$; $v_{\mathrm{PW2}}\left(K_{\mathrm{PW2},T_{\mathrm{PA2},in}}\right)$ is the velocity-density relationship of the passageway2. According to the relevant description of service level, when $K_{\mathrm{PW2},T}$ does not exceed the threshold $K_{\mathrm{PW2},init}$, passengers2 in passageway2 can maintain a free-flow state. Therefore, if $v_{\mathrm{PW2},init}$ is set as the free-flow speed of the passageway2, its velocity-density relationship at time T is shown in *Equation 5*.

$$v_{\mathrm{PW2}}\left(K_{\mathrm{PW2},T}\right) = \begin{cases} v_{\mathrm{PW2},init} & K_{\mathrm{PW2},T} \le K_{\mathrm{PW2},init} \\ f\left(K_{\mathrm{PW2},T} - K_{\mathrm{PW2},init}\right) & K_{\mathrm{PW2},T} > K_{\mathrm{PW2},init} \end{cases} \tag{5}$$

Similar to passageway2, subarea3 is also a horizontal passage, and passengers leave the area after swiping the card or scanning the code. Therefore, the basic transit time of passengers1 and passengers2 in subarea3 should add swiping time or scanning time t_{s} to the travel time, as shown in *Equation 6 and 7*, respectively;

$$t_{\mathrm{PA1,SA3}} = \frac{L_{\mathrm{PW1,GA}}}{v_{\mathrm{SA3}}\left(K_{\mathrm{SA3},T_{\mathrm{SA3,PA1},in}}\right)} + t_{\mathrm{s}} \tag{6}$$

$$t_{\mathrm{PA2,SA3}} = \frac{L_{\mathrm{PW2,GA}}}{v_{\mathrm{SA3}}\left(K_{\mathrm{SA3},T_{\mathrm{SA3,PA2},in}}\right)} + t_{\mathrm{s}} \tag{7}$$

where: $t_{\mathrm{PA1,SA3}}$ is the basic transit time of passengers1 in subarea3. $t_{\mathrm{PA2,SA3}}$ is the basic transit time of passengers2 in subarea3. $L_{\mathrm{PW1},GA}$ is the distance from passageway1 to the gate unit. $L_{\mathrm{PW2},GA}$ is the distance from passageway2 to the gate unit. $T_{\mathrm{SA3,PA1},in}$ and $T_{\mathrm{SA3,PA2},in}$ are respectively the time when passengers1 and passengers2 enter the subarea3. $K_{\mathrm{SA3},T_{\mathrm{SA3,PA1},in}}$ and $K_{\mathrm{SA3},T_{\mathrm{SA3,PA2},in}}$ are respectively the passenger density of the subarea3 at time $T_{\mathrm{SA3,PA1},in}$ and $T_{\mathrm{SA3,PA2},in}$. $v_{\mathrm{SA3}}(\bullet)$ is the velocity-density relationship of the subarea3. According to the relevant description of service level, when $K_{\mathrm{SA3},T}$ does not exceed the threshold $K_{\mathrm{SA3},init}$, passengers can maintain a free-flow state. Therefore, if $v_{\mathrm{SA3},init}$ is set as the free-flow speed of the subarea3, its velocity-density relationship at time T is shown in *Equation 8*.

$$v_{\mathrm{SA3}}\left(K_{\mathrm{SA3},T}\right) = \begin{cases} v_{\mathrm{SA3},init} & K_{\mathrm{SA3},T} \le K_{\mathrm{SA3},init} \\ g\left(K_{\mathrm{SA3},T} - K_{\mathrm{SA3},init}\right) & K_{\mathrm{SA3},T} > K_{\mathrm{SA3},init} \end{cases} \tag{8}$$

2.2 Quantitative method of additional transit time

Due to the limitation of security inspection capability, passengers1 in subarea1 may wait in line in front of passageway1. It will make their actual transit time in subarea1 longer than their normal transit time and then generate additional transit time.

Because of the limited number of passengers in passageway1, if the number of passengers allowed to enter the passageway1 at time T $D_{\mathrm{PW1},in,T}$ is not less than the number of passengers who plan to enter the passageway1 at any time T, these passengers can enter the passageway1 immediately, and the additional transit time remains unchanged. Otherwise, passengers1 who can enter passageway1 should be determined according to the passenger index and the additional transit time of passengers1 who cannot enter passageway1 should be increased by 0.1 s, indicating temporary waiting;

$$D_{\mathrm{PW1},in,T} = \frac{L_{SE}}{H} - D_{\mathrm{PW1},T} \tag{9}$$

where H is the passenger static thickness; $D_{\mathrm{PW1},T}$ is the number of passengers in passageway1 at T.

To determine the additional transit time of passengers2 in subarea1, it is necessary to consider the width of passageway2 and its passenger density.

Passengers2 from subarea1 will generally enter the passageway2 side by side. When the sum of the body widths of these passengers exceeds the width of the passageway2, that is, when *Equation 10* is met, only a part of passengers2 can enter passageway2, and their additional transit time will not change; other passengers2 need to wait, and their additional transit time should be increased by 0.1 s;

$$W_{\mathrm{PW2}} \le D_{\mathrm{PW2},T} W_{\mathrm{B}} \tag{10}$$

where W_{PW2} is the width of passageway2; $D_{\mathrm{PW2},T}$ is number of passengers2 in passageway2 at T; W_{B} is the body width.

When the passenger density in the passageway2 increases and it is unable to accommodate all passengers2 from subarea1 entering the passageway2, passengers will queue up in front of passageway2. At time T, the number of passengers2 that can be accommodated in the remaining space of the passageway2 $D_{\mathrm{PW2},in,T}$ is shown in *Equation 11*

$$D_{\mathrm{PW2},in,T} = A_{\mathrm{PW2}}\left(K_{\mathrm{PW2},max} - K_{\mathrm{PW2},T}\right) \tag{11}$$

where: A_{PW2} is the area of passageway2; $K_{\mathrm{PW2},max}$ is the allowed maximum density of passageway2.

If $D_{\mathrm{PW2},in,T}$ is not less than the number of passengers who plan to enter the passageway2 at *T*, these passengers can enter the passageway2 immediately, and the additional transit time remains unchanged. Otherwise, passengers2 who can enter passageway2 should be determined according to the passenger index and the additional transit time of passengers2 who cannot enter passageway2 should be increased by 0.1 s.

When the passenger density in subarea3 increases and it is unable to accommodate all passengers from subarea2, passengers will queue up in front of subarea2.

If the number of passengers allowed to enter subarea3 $D_{\mathrm{SA3},in,T}$ is not less than the number of passengers who plan to enter subarea3 at any time T, these passengers can enter subarea3 immediately, and the additional transit time remains unchanged. Otherwise, passengers1 who can enter subarea3 should be determined according to the passenger index and the additional transit time of passengers who cannot enter subarea3 should be increased by 0.1 s;

$$D_{\mathrm{SA3},in,T} = A_{\mathrm{SA3}}\left(K_{\mathrm{SA3},max} - K_{\mathrm{SA3},T}\right) \tag{12}$$

where A_{SA3} is the area of subarea3. $K_{\mathrm{SA3},max}$ is the allowed maximum density of passengers in subarea3.

When passengers queue up in front of the gate unit, the passengers in subarea3 cannot reach the gate unit immediately, which causes them to delay passing through subarea3 and generates additional passing time.

For each gate, after one passenger enters the gate, the next one can continue to enter the gate. Therefore, when the number of passengers who plan to pass through the gate unit is not greater than the number of access gates, these passengers will enter the pay area immediately, and the additional transit time in subarea3 will remain unchanged; otherwise, passengers who can enter the pay area should be determined according to the passenger index and the additional transit time of passengers who cannot enter the pay area should be increased by 0.1 s.

2.3 Passenger flow recursion process

The calculation of the basic transit time and additional transit time needs to clarify the passenger flow status of the corresponding subarea at each moment in the passenger access/egress process, as shown in the next part of this article.

Input the value of the parameters described above. Input the number of gates N_G. Determine the specific function form of v_{PW2} and v_{SA3}, and input relevant parameters. Determine the total number of passengers entering the station D_{All}, as well as the number of passengers1 and passengers2 departing from the entrance at ≥ 0, and number the passengers according to the time sequence, in which passengers departing at the same time are numbered alternately according to the order of passengers1 and passengers2. The subsequent steps are depicted in *Figure 3*, and the required variables are defined in *Table 1*.

Table 1 – The required variables definitions in the passenger flow recursion process

Required variables	Variable definition
D_{pass}	Total number of people passing the security inspection and ticket-checking area
$U_{\mathrm{SA1,PW1},T}$	Passenger collection to enter the passageway1 from subarea1
$U_{\mathrm{SA1,PW2},T}$	Passenger collection to enter the passageway2 from subarea1
$U_{\mathrm{PW1,SA3},T}$	Passenger collection to enter subarea3 from the passageway1
$U_{\mathrm{SA3,GA},T}$	Passenger collection to enter the pay area from subarea3
$t_{\mathrm{PA1,SA1},i}$	Basic transit time of passenger i who refers to passengers1 in subarea1
$t_{\mathrm{PA2,SA1},i}$	Basic transit time of passenger i who refers to passgeners2 in subarea1
$t_{\mathrm{SA1},Add,i}$	Additional transit time of passenger i in subarea1
$t_{\mathrm{PA1,PW1},i}$	Basic transit time of passenger i who refers to passengers1 in the passageway1
$t_{\mathrm{PA2,PW2},i}$	Basic transit time of passenger i who refers to passengers2 in the passageway2
$t_{\mathrm{SA2},Add,i}$	Additional transit time of passenger i in subarea2
$t_{\mathrm{PA1,SA3},i}$	Basic transit time of passenger i who refers to passengers1 in subarea3
$t_{\mathrm{PA2,SA3},i}$	Basic transit time of passenger i who refers to passengers2 in subarea3
$t_{\mathrm{SA3},Add,i}$	Additional transit time of passenger i in subarea3

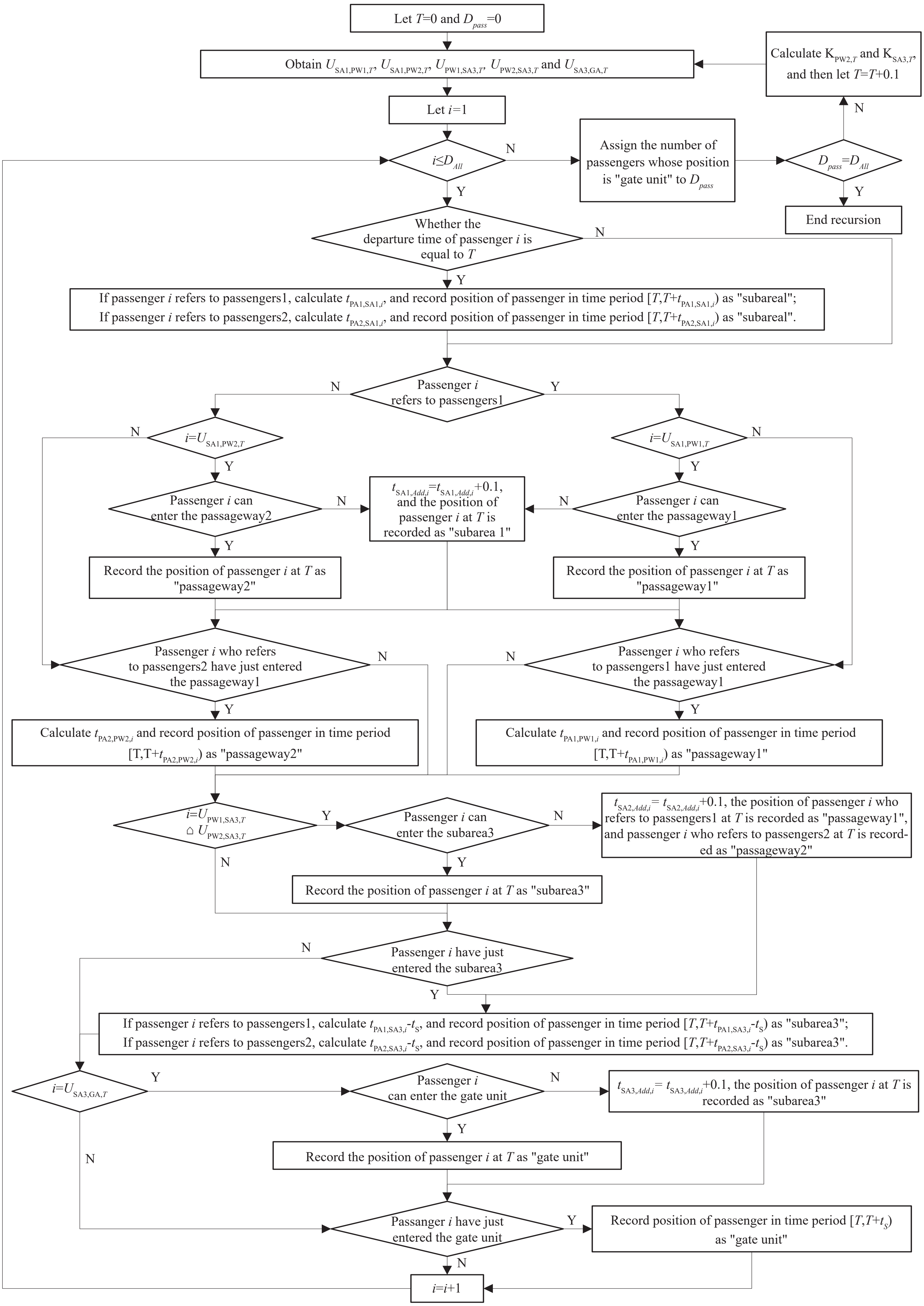


Figure 3 – Passenger flow recursion process flow chart

2.4 Calculation methods of expected output indicators

The calculation methods of expected output indicators are as follows.

Through the above recursive process, the direct results are the position of each passenger at *T*, including subarea1, passageway1, passageway2, subarea3 and gate unit. The passenger access/egress process starts with the first passenger coming into subarea1 and ends with the last passenger leaving the gate unit. Therefore, the passenger access/egress time should be calculated according to this idea.

The average transit time of passengers1 $\overline{t_{\mathrm{PA1}}}$ and passengers2 $\overline{t_{\mathrm{PA2}}}$ can be calculated as follows:

$$\overline{t_{\mathrm{PA1}}}=\frac{1}{D_{\mathrm{PA1}}}\sum_{i\in U_{\mathrm{PA1}}}\left(t_{\mathrm{PA1,SA1},i}+t_{\mathrm{SA1},Add,i}+t_{\mathrm{PA1,SA2},i}+t_{\mathrm{SA2},Add,i}+t_{\mathrm{PA1,SA3},i}+t_{\mathrm{SA3},Add,i}+t_{\mathrm{s}}\right) \tag{13}$$

$$\overline{t_{\mathrm{PA2}}}=\frac{1}{D_{\mathrm{PA2}}}\sum_{i\in U_{\mathrm{PA2}}}\left(t_{\mathrm{PA2,SA1},i}+t_{\mathrm{SA1},Add,i}+t_{\mathrm{PA2,SA2},i}+t_{\mathrm{SA2},Add,i}+t_{\mathrm{PA2,SA3},i}+t_{\mathrm{SA3},Add,i}+t_{\mathrm{s}}\right) \tag{14}$$

where D_{PA1} is the number of passengers1. D_{PA2} is the number of passengers2. U_{PA1} is the collection of passengers1. U_{PA2} is the collection of passengers2.

If a passenger i who refers to passengers1 meets $t_{\mathrm{SA1},Add,i}>0$, the passenger has waited in line in front of passageway1 for a period $\left[T+t_{\mathrm{PA1,SA1},i},T+t_{\mathrm{PA1,SA1},i}+t_{\mathrm{SA1},Add,i}\right)$. The number of passengers queuing up in front of passageway1 at time T is equal to the number of all periods that meet $T\in\left[T+t_{\mathrm{PA1,SA1},i},T+t_{\mathrm{PA1,SA1},i}+t_{\mathrm{SA1},Add,i}\right)$.

Similar to the number of passengers queuing up in front of passageway1, the number of passengers2 in passageway2 at time T is equal to the number of all periods that meet $T\in\left[T+t_{\mathrm{PA2,SA1},i}+t_{\mathrm{SA1},Add,i},\ T+t_{\mathrm{PA2,SA1},i}+t_{\mathrm{SA1},Add,i}+t_{\mathrm{PA2,SA2},i}+t_{\mathrm{SA2},Add,i}\right)$. When A_{PW2} is known, the passenger flow density of passageway2 can be easily calculated. As long as passengers1 and passengers2 are distinguished, the passenger flow density of the subarea3 can be calculated in the same way.

3. CASE STUDY

3.1 Case scenario design

Take *Figure 1* as an example of the layout of the security inspection and ticket-checking area. The distance between subareas is calculated by the midpoint distance of the adjacent sections of the subareas. The values of parameters described above are shown in *Table 2*. $f\left(K_{\mathrm{PW2},T}-K_{\mathrm{PW2},init}\right)$ in *Equation 5* and $g\left(K_{\mathrm{SA3},T}-K_{\mathrm{SA3},init}\right)$ in *Equation 8* use the same function form, that is, if set $x=K_{\mathrm{PW2},T}-K_{\mathrm{PW2},init}$, the function form of $f\left(K_{\mathrm{PW2},T}-K_{\mathrm{PW2},init}\right)$ is $0.11x^3-0.53x^2+0.15x+1.61$; if set $y=K_{\mathrm{SA3},T}-K_{\mathrm{SA3},init}$, the function form of $g\left(K_{\mathrm{SA3},T}-K_{\mathrm{SA3},init}\right)$ is $0.11y^3-0.53y^2+0.15y+1.61$ [26]

Table 2 – The value of input parameters

Input parameter	Value	Input parameter	Value
$L_{EN,\mathrm{PW1}}$ [m]	5.36	$K_{\mathrm{PW2},init}$ [ped/m^2]	0.31
$L_{EN,\mathrm{PW2}}$ [m]	4.69	$K_{\mathrm{SA3},init}$ [ped/m^2]	0.31
L_{PW2} [m]	4.55	v_0 [m/s]	1.61
L_{SE} [m]	2.3	v_{SE} [m/s]	0.2
$L_{\mathrm{PW1},GA}$ [m]	3.65	$v_{\mathrm{PW2},init}$ [m/s]	1.61
$L_{\mathrm{PW2},GA}$ [m]	4.07	$v_{\mathrm{SA3},init}$ [m/s]	1.61
A_{PW2} [m^2]	10.2	t_{pi} [s]	2.0
A_{SA3} [m^2]	21.8	t_{ti} [s]	2.0
$K_{\mathrm{PW2},max}$ [ped/m^2]	3.5	t_S [s]	3.5
$K_{\mathrm{SA3},max}$ [ped/m^2]	3.5	N_G	5

The passenger flow situations are designed as shown in *Table 3*. The duration of passenger flow is divided into two situations: (1) the passenger flow continues to enter the station with the same passenger flow in 0–60 s; (2) the passenger flow continues to enter the station with the same passenger flow in 0–25 s and 36–70 s, and the passenger flow in other periods is 0. The total passenger flow in this case is the same as that in Group 1. The conditions of 10 groups are shown in *Table 4*.

Table 3 – The passenger flow of passengers1 and passengers2

Situation	Passenger flow of passengers1 [ped/s]	Passenger flow of passengers2 [ped/s]
1	1	5
2	2	4
3	3	3
4	4	2
5	5	1

Table 4 – The conditions of 10 groups

<table>
<tr><th>Group</th><th>Passenger flow</th><th>Duration of passenger flow</th><th>Group</th><th>Passenger flow</th><th>Duration of passenger flow</th></tr>
<tr><td>1</td><td>Situation 1</td><td rowspan="5">Situation 1</td><td>6</td><td>Situation 1</td><td rowspan="5">Situation 2</td></tr>
<tr><td>2</td><td>Situation 2</td><td>7</td><td>Situation 2</td></tr>
<tr><td>3</td><td>Situation 3</td><td>8</td><td>Situation 3</td></tr>
<tr><td>4</td><td>Situation 4</td><td>9</td><td>Situation 4</td></tr>
<tr><td>5</td><td>Situation 5</td><td>10</td><td>Situation 5</td></tr>
</table>

3.2 Calculation results

To ensure the flexibility of method adjustment, the calculation software was written using C#.NET according to the recursive process shown in Chapter 2.3. The passenger access/egress time, average transit time of passengers1 and average transit time of passengers2 of 10 groups are shown in *Table 5*.

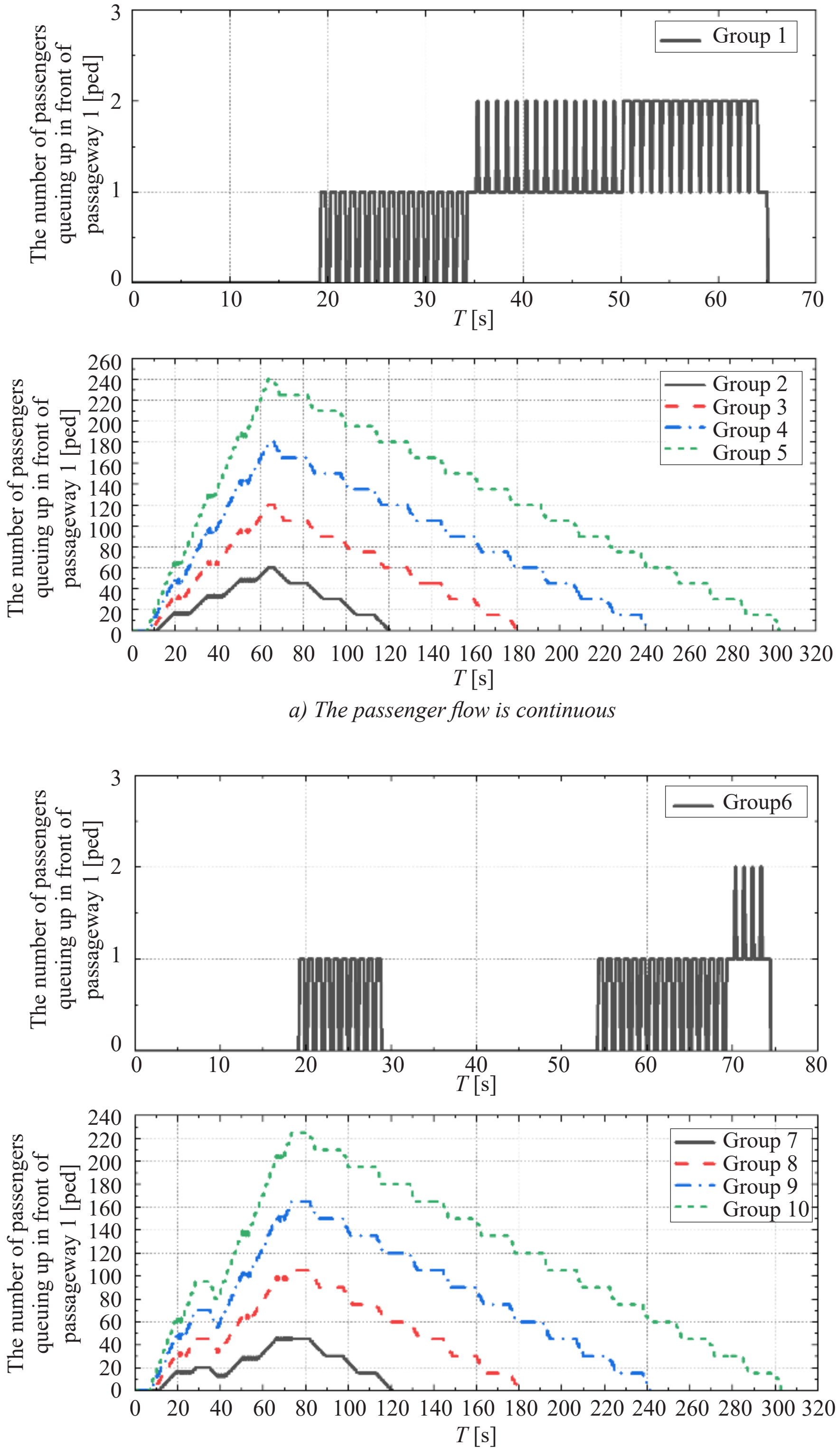
Table 5 – The passenger access/egress time, the average transit time of passengers1 and passengers2

Group	Access/egress time [s]	Average transit time of passengers1 [s]	Average transit time of passengers2 [s]
1	83	25.5	12.5
2	138.4	53	11.8
3	197.8	82.9	11.7
4	259.2	113.5	11.7
5	320.6	144.3	11.7
6	92.4	25.0	12.5
7	138.4	47.1	11.8
8	197.8	77.1	11.7
9	259.2	107.7	11.7
10	320.6	138.5	11.7

The following conclusions are as follows.

1) With the increase in the proportion of passengers1, the average transit time of passengers1 increases significantly, and the access/egress time is also significantly increased.
2) Compared with the average transit time of passengers1, the average transit time of passengers2 is relatively small.

3) Under the same total passenger flow, the interruption of passenger flow for a period of time has a certain impact on the average transit time of passengers1. Except for Situation 1 of passenger flow, the average transit time of passengers1 with interruption can be reduced by 5.7–5.9 s compared with the situation with no interruption. The reason is that the number of pedestrian queuing before the passageway1 decreases during the interruption of passenger flow, which makes the overall queuing time decrease after the recovery of passenger flow. However, due to the limited capacity of the passageway1, the queuing passenger flow rapidly accumulates, resulting in the limited reduction of the average transit time of passengers1.



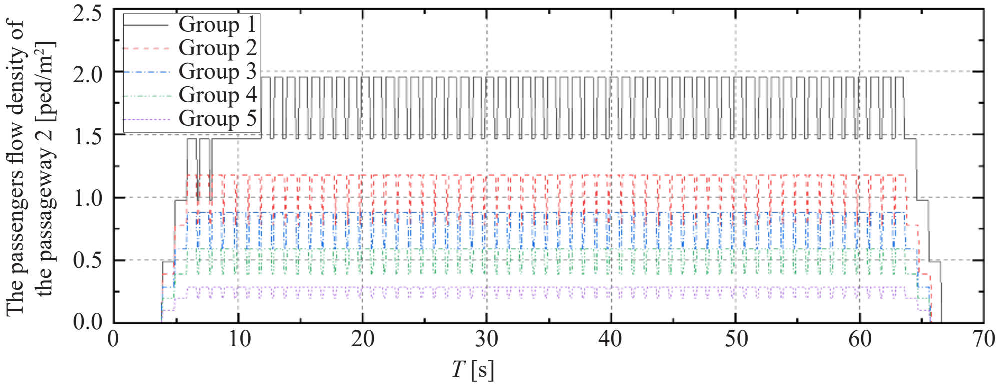
a) The passenger flow is continuous

b) The passenger flow is discontinuous

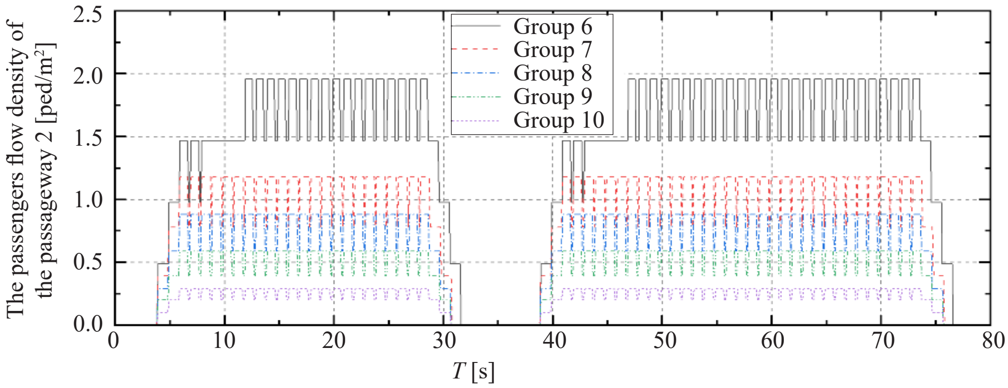
Figure 4 – The number of passengers queuing up in front of passageway1 under two condition

During the access/egress process, the number of passengers queuing up in front of passageway1 and the passenger flow density of passageway2 under the two conditions of uninterrupted and intermittent passenger flow is shown in *Figure 4* and *Figure 5*. The comparison of passenger flow density in subarea3 is shown in *Figure 5*.

It can be seen from *Figure 4* that the peak number of passengers queuing in front of the passageway1 when the passenger flow is interrupted is significantly lower than that when the passenger flow is uninterrupted. It can be seen from *Figure 6* that when the passenger flow is interrupted, compared with the situation of uninterrupted passenger flow, although the peak passenger flow density in passageway2 has not changed, there is an obvious clearing period for the passenger flow. It can be seen from *Figure 5* that compared with the uninterrupted passenger flow, the main range of passenger flow density under the discontinuous passenger flow is relatively low.

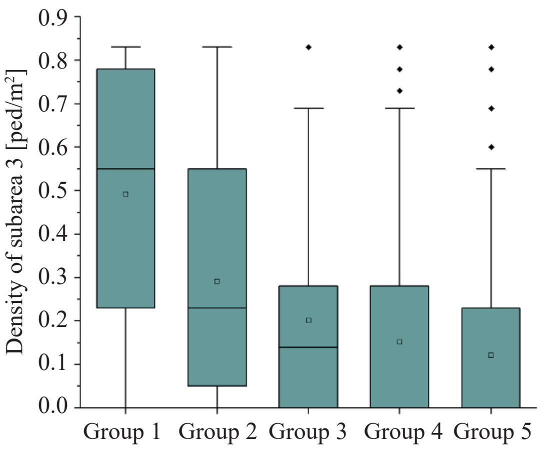


a) The passenger flow is continuous

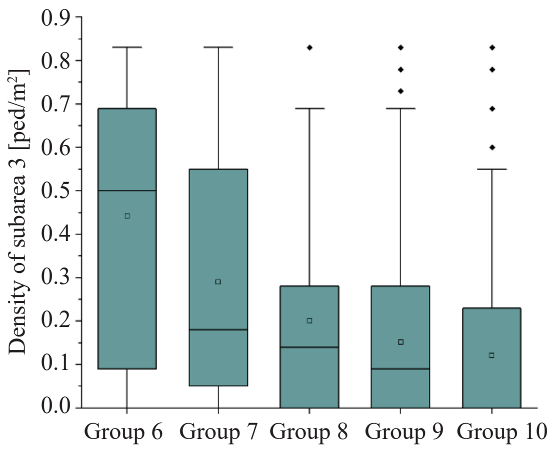


b) The passenger flow is discontinuous

Figure 5 – The passenger flow density of the passageway2 under two conditions



a) The passenger flow is continuous



b) The passenger flow is discontinuous

Figure 6 – The comparison of passenger flow density in subarea3 under two conditions

4. DISCUSSIONS

During the formation of the method described in this paper, three main factors may have a large impact on the accuracy of the results: (1) dependence on the velocity-density relationship; (2) the division of passageway1 and passageway2 in subarea2; and (3) the passenger numbering strategy. These three factors are discussed separately below.

4.1 Dependence on the velocity-density relationship

The calculation of transit times in passageway2 and subarea3 depends on the velocity-density functions of the corresponding areas. The velocity-density function exists in various forms such as cubic polynomial, quadratic polynomial and exponential function. The coefficients in each of these forms also vary with the data acquisition scenarios. The calculation results of the method in the same scenario are likely to change after changing the function form or the value of coefficients. Therefore, the dependence on the velocity-density function is one of the limitations of this method.

4.2 Division of passageway1 and passageway2 in subarea2

The following setting is implied, that is, passengers1 walk in passageway1 and passengers2 walk in passageway2, which are not in conflict with each other. If no railing is placed between them, it is theoretically possible for passengers2 to occupy passageway1. However, the above-mentioned situation occurs only during the non-peak hours, and the choice of passengers during the peak hours usually follows the above-mentioned setting. From this perspective, the division between passageway1 and passageway2 does not affect the calculation results.

4.3 Influence of passenger numbering strategy

The passenger numbering strategy should be analysed in greater detail. Different strategies may have an impact on the model results. In the above cases, for passengers who leave at the same time, the strategy of numbering passengers1 and passengers2 in turn is adopted. The strategy can be called Strategy1. In addition, there are three other strategies as follows: (1) number passengers2 and passengers1 in turn (called Strategy2); (2) number passengers1 first, and then number passengers2 (called Strategy3); (3) number passengers2 first, and then number passengers1 (called Strategy4). For example, if there are 3 passengers who refer to passengers1 (named A1, A2 and A3) and 3 passengers who refer to passengers2 (named B1, B2 and B3). They are leaving from the entrance at the same time. Under the above four numbering strategies, their numbers are shown in *Table 6*.

Table 6 – The numbers of 6 passengers under the above four numbering strategies

Passenger	Passenger numbers			
	Strategy1	Strategy2	Strategy3	Strategy4
A1	1	2	1	4
A2	3	4	2	5
A3	5	6	3	6
B1	2	1	4	1
B2	4	3	5	2
B3	6	5	6	3

The passenger access/egress time, average transit time of passengers1 and average transit time of passengers2 for Group 2 and Group 3 under Strategy2, Strategy3 and Strategy4 are shown in *Table 7*. From the comparison between *Table 7* and *Table 5*, the passenger numbering strategy has little influence on the analysis results.

Table 7 – The passenger access/egress time, the average transit time of passengers1 and passengers2 of Group 2 and Group 3 under Strategy2, Strategy3 and Strategy4

Strategy	Group	Access/egress time [s]	Average transit time of passengers1 [s]	Average transit time of passengers2 [s]
2	2	138.3	53.0	11.8
2	3	197.7	82.9	11.7
3	2	138.3	53.0	11.8
3	3	197.7	82.9	11.7
4	2	138.3	53.0	11.8
4	3	197.7	82.9	11.7

5. CONCLUSIONS

The proposed method in this paper considers the security inspection area jointly with the entrance gate unit while distinguishing whether passengers are carrying bags or not. It can not only avoid the tedious and time-consuming scene construction process of the microsimulation software but also reflect the dynamic changes of the whole process of passenger distribution. When the scheme of security inspection and ticket-checking area changes, the change scheme can be analysed as long as the input parameter values are changed.

This method also has the following shortcomings:

1) The accuracy of the method depends to some extent on the velocity-density relationship of passageway2 and subarea3, i.e. different speed-density relationships in the above regions may lead to different queuing congestion results.
2) The paper takes the case that the passenger flow in the security inspection and ticket-checking area comes from one entrance and exit as an example, that is, the method described herein is only applicable to the case shown in *Figure 1*.

In the future, we will further determine the specific form of the velocity-density function of passageway2 and subarea3 and build the corresponding congestion analysis methods for different types of security inspection and ticket-checking areas.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Liao M, Liu G. Modelling passenger behavior in non-payment areas at rail transit stations. *Transportation Research Record.* 2015;2534:101-108. DOI: 10.3141/2534-13.

[2] Liao M, Liu G, Qiu T. Passenger traffic characteristics of service facilities in rail transit stations of Shanghai. *Journal of Transportation Engineering.* 2013;139(2):223-229. DOI: 10.1061/(ASCE)TE.1943-5436.0000481.

[3] He B, Gu B. Passenger flow assignment algorithm and software implementation of pedestrian streamline network of urban mass transit station. *Journal of Tongji University (Natural Science edition)* 2018;46(8):1089-1097. DOI: 10.11908/j.issn.0253-374x.2018.08.012.

[4] Soltani E, Kashi, E. Pedestrian simulation and PLOS analysis in the subway station. *Innovative Infrastructure Solutions* 7. 2022. DOI: 10.1007/s41062-021-00662-2.

[5] Hoogendoorn SP, Hauser M, Rodrigues N. Applying microscopic pedestrian flow simulation to railway station design evaluation in Lisbon, Portugal. *Transportation Research Record.* 2004;1878:83-94. DOI: 10.3141/1878-11.

[6] Zhao G, Zhang G, Chen Y, Ping, W. Pedestrian simulation research of subway station in special events. *ICCTP 2009: Critical Issues in Transportation Systems Planning, Development, and Management, Proceedings of Ninth International Conference of Chinese Transportation Professionals, ICCTP 2009, 5-9 Aug. 2009, Harbin, China*. Reston: American Society of Civil Engineers (ASCE); 2009. p. 1351-1358.

[7] Lei W, et al. Simulation of pedestrian crowds' evacuation in a huge transit terminal subway station. *Physica A: Statistical Mechanics and its Applications*. 2012;391(22):5355-5365. DOI: 10.1016/j.physa.2012.06.033.

[8] King D, Srikukenthiran S, Shalaby A. Using simulation to analyze crowd congestion and mitigation at Canadian subway interchanges: Case of Bloor-Yonge Station, Toronto, Ontario. *Transportation Research Record.* 2014;2417:27-36. DOI: 10.3141/2417-04.
[9] Yang Y, Li J, Zhao Q. Study on passenger flow simulation in urban subway station based on Anylogic. *Journal of Software*. 2014;9(1):140-146.
[10] Hoy G, Morrow E, Shalaby A. Use of agent-based crowd simulation to investigate the performance of large-scale intermodal facilities: Case study of union station in Toronto, Ontario, Canada. *Transportation Research Record*. 2016;2540:20-29. DOI: 10.3141/2540-03.
[11] Chen X, et al. A multiagent-based model for pedestrian simulation in subway stations. *Simulation Modelling Practice and Theory*. 2017;71:134-148. DOI: 10.1016/j.simpat.2016.12.001.
[12] Ni W, et al. Study on optimization of passenger flow at a metro station based on AnyLogic: Case study of Youfangqiao Station of Nanjing metro line 2. *Complex System Modelling and Simulation*. 2021;1(3):242-252. DOI: 10.23919/CSMS.2021.0009.
[13] Zhu Q. Passenger flow simulation of Xiamafang metro station based on AnyLogic. *Highlights in Science, Engineering and Technology*. 2023;37:142-156. DOI: 10.54097/hset.v37i.6069.
[14] Kim JY, Kim, YO. Analysis of pedestrian behaviors in subway station using agent-based model: Case of Gangnam Station, Seoul, Korea. *Buildings*. 2023;13:537. DOI: 10.3390/buildings13020537.
[15] Lin X, Cheng L, Zhang S, Wang Q. Simulating the effects of gate machines on crowd traffic based on the modified social force model. *Mathematics.* 2023;11:780. DOI: 10.3390/math11030780.
[16] Yamada T, Utaka M. Evaluating ticket gate directional restrictions using simulations of pedestrian flow considering stationary people in a railroad station concourse. *Journal of Asian Architecture and Building Engineering*. 2023;22(4):2058-2073. DOI: 10.1080/13467581.2022.2153063.
[17] Marin DV, Bachar K, Fabien L. On pedestrian traffic management in railway stations: Simulation needs and model assessment. *Transportation Research Procedia*. 2019;37:3-10. DOI: 10.1016/j.trpro.2018.12.159.
[18] Guo C, Gu B. Network creation and travel time calculation of pedestrian flow in urban mass transit station. *Journal of Tongji University (Natural Science)*. 2014;42(3):429-434+440. DOI: 10.3969/j.issn.0253-374x.2014.03.016.
[19] Guo C. *Network creation and travel time calculation of pedestrian flow in urban rail transit station*. PhD thesis. Tongji University; 2016.
[20] Jiang Y, Luo N. Urban rail transit station automatic fare collection configuration research and simulation. *ICTE 2013: Safety, Speediness, Intelligence, Low-Carbon, Innovation: Proceedings of the Fourth International Conference on Transportation Engineering*, *ICTE 2013*, *19-20 Oct. 2013*, *Chengdu*, *China*. Reston: American Society of Civil Engineers (ASCE); 2013. p. 1142-1149.
[21] Xu X, Liu J, Li H, Hu J. Analysis of subway station capacity with the use of queueing theory. *Transportation Research Part C: Emerging Technologies*. 2014;38(1):28-43. DOI: 10.1016/j.trc.2013.10.010.
[22] Khattak A, Jiang Y, Zhu J, Hu L. A new simulation-optimization approach for the circulation facilities design at urban rail transit station. *Archives of Transport*. 2017;43(3):69-90. DOI: 10.5604/01.3001.0010.1795.
[23] Zhang X. *The study of optimization method to the allocation of automatic ticket checking machine in subway station*. MA thesis. Changan University; 2018.
[24] Liu J, He S, Zhang H. Optimization analysis for serial bottleneck system of urban rail transit station. *Journal of Computer Applications*. 2016;36(1):271-274+286. DOI: 10.11772/j.issn.1001-9081.2016.01.0271.
[25] Tang G. *Research on optimization of the allocation of double-check system for urban rail transit*. MA thesis. Changan University; 2020.
[26] Cao S. *Analysis and modelling on passengers traffic characteristics for urban rail transit*. PhD thesis. Beijing Jiaotong University; 2009.

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地铁站内无安检门的安检-检票区域客流排队分析方法

摘要
为了避免进站检票机前的拥堵，需要在规划设计阶段对其排队情况进行分析优化。本文将安检区域和检票区域共同考虑，提出了一种客流排队分析方法。首先，阐述了研究问题。然后，将每个子区域中任意时刻的乘客数量计算问题转化为每个子分区中每个乘客的通过时间计算问题。通过时间分为基本通过时间和附加通过时间。基于速度-密度关系，提出了一种与乘客到达时间相关的基本通过时间量化方法。附加通过时间根据乘客到达的顺序、排队乘客人数和进入子区域时的拥堵情况确定。最后，通过客流递推得到任意时刻下各子区域乘客排队情况。算例表明，该方法不仅可以适应多种工作条件，而且还能够避免微观仿真软件繁琐、耗时的场景构建过程。

关键词
地铁车站；安检区域；检票区域；客流排队；通过时间；客流递推.