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COMPARATIVE ANALYSIS AND PEDESTRIAN SIMULATION EVALUATION ON EMERGENCY EVACUATION TEST METHODS FOR URBAN RAIL TRANSIT STATIONS

ABSTRACT

The emergency evacuation test method of rail transit station not only affects the operation safety of the station, but it also has significant influence on the scale and cost of the station. A reasonable test method should guarantee both the safety of evacuation and that the investment is neither excessive nor too conservative. The paper compares and analyzes the differences of the existing emergency evacuation test methods of rail stations in China and other regions on the evacuation load, evacuation time calculation and the capacity of egress components, etc. Based on the field survey analysis, the desired velocity distribution of pedestrians in various station facilities and the capacity of egress components have been obtained, and then the parameters of pedestrian simulation tool were calibrated. By selecting a station for the case study, an evacuation simulation model has been established, where five evacuation scenarios have been set according to different specifications and the simulation results have been carefully analyzed. Through analyzing the simulation results, some modification proposals of the current emergency evacuation test method in the design manual have been considered, including taking into account the section passenger volume, walking time on escalators and stairs of the platform, and the condition in which the escalator most critical to evacuation should be considered as out of service.

KEY WORDS

urban rail transit, station, emergency evacuation, comparison, pedestrian simulation

1. INTRODUCTION

As passenger distribution nodes, stations of urban rail transit are one of the public buildings with the highest pedestrian density. Furthermore, stations, especially the underground ones, have closed environments and varied facilities, where passenger's walking behavior is complicated, so in case of fire, toxic gases or other human-caused accidents, the passenger evacuation will face great challenges. If the evacuation is not timely, the consequences will be disastrous [1]. Therefore, the relevant design specifications or manuals of stations in China and other countries specify that the scale and layout of the distribution facilities at stations should not only be calculated using passenger load under normal conditions, but they should also be checked to determine if they can meet the demand of emergency evacuation. However, the regulations of design method for emergency evacuation, including the calculation methods of evacuation load, facility evacuation capacity per unit width and evacuation time, etc., are quite different among the design specifications of different countries and regions [2]. For the same station with the same passenger volume, the results obtained by different test methods are quite different. Therefore, it is necessary to conduct a comparative analysis and evaluation on these test methods so as to provide proposals for establishing a secure and economical check calculation method.

2. COMPARISON OF EMERGENCY EVACUATION TEST METHODS IN DIFFERENT REGIONS

Design specifications and manuals are the main embodiment at practice level of the relevant research. This paper chooses three typical specifications and manuals about test methods of emergency evacuations of urban rail transit station, and takes a comparative analysis on the load of evacuees, facility evacuation capacity and evacuation time calculation methods of these design specifications and manuals. The three specifications respectively are the "*Code for the Design of Metro*" [3] of Mainland China (2003 edition, hereinafter referred to as "*Code*"), the "*Underground Station Design Guideline of MRT*" [4] of Taiwan (hereinafter referred to as "*Guideline*"), and the "*NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems*" [5] of the USA (2007 edition, hereinafter referred to as the "*Standard*").

2.1 "*Code*" of Mainland China

The evacuation test method in the "Code" is relatively simple. In accordance with the relevant provisions, all the passengers and staff on the platform should be evacuated from the platform within 6 minutes (including 1-minute reaction time). The time test formula is:

$$T = 1 + \frac{Q_1 + Q_2}{0.9[A_1(N-1) + A_2 B]} \quad (1)$$

In the formula, Q_1 denotes crush load of a train; Q_2 is entraining load and staff on the platform; A_1 for capacity of unit width escalator (person /(min·m)); A_2 refers to capacity of unit width stairway (person / (min·m)); N is quantity of escalators; B means total width of all the stairways.

The occupant load consists of the entraining load in a headway and the workers on the platform when emergency happens and a fully loaded train arrives in the station. Considering that the total width of stairways influences the scale of the platform and the distribution capacity of the escalators, it is assumed that one escalator is out of service but the working escalators are still used as egress route. The facility evacuation capacity is not specified. According to the design material of the designing institute, the evacuation capacity still adopts the capacity under normal operation condition, where escalator evacuation capacity is 150 persons/(min·m) and the stairways evacuation capacity is 62 persons/(min·m). Counting in panic influence, the evacuation capacities are deducted by 10 percent.

2.2 "*Standard*" of USA

The "*Standard*" sets two requirements on emergency evacuation: first, empty the platform in four minutes; second, the most remote passengers to the exits can move to the safe place within six minutes. The following formula is used to calculate the platform evacuation time:

$$F_p = \frac{Q_p}{C_p} \leq 4\,\text{min} \quad (2)$$

where Q_p is occupant load on the platform; C_p refers to platform facility evacuation capacity

Provisions 5.5.5.6 and 5.5.6.2 of the "*Standard*" describe the evacuees on the platform and the facility evacuation capacity in detail. There is no formula to calculate the occupants load but it stipulates that the passengers awaiting on the platform and the passengers in the train need to be considered. The volume of passengers in the train is determined according to the combination of the headway in peak hours and such factors as the unpunctuality rate and the system reaction time, etc. For the facility evacuation capacity, the escalator is considered as stairways, and it is assumed that the escalator most critical for evacuation is out of service, and the escalators take the evacuation of no more than half of the passengers except in specified conditions.

For the evacuation time from the most remote point of the platform to a safe place, the "*Standard*" does not give a definite formula, but rather just stipulates that the concourse level in a different fireproof partition can be taken as a safe place, considering the walking time on the facilities and the waiting time at the bottleneck facilities. According to the example given by the "*Standard*", if taking the entrance/exit as the safe place, the total evacuating time can be calculated as follows:

$$T_{total} = \sum_{i=1}^{m} T_i + \sum_{j}^{n} W_j \quad (3)$$

where: T_i - denotes Walking time on the circulation facility i, including platform, stairways, concourse level, and fare collection equipment; W_j - is the waiting time at the bottleneck facility j.

Take the calculation of W_p for example, which is the waiting time at the exit of the stairways and escalators:

$W_p = F_p - T_p$, and F_p means platform evacuation time, calculation formula shown as formula (2); T_p is walking time from the most remote point to its nearest stairway exit.

Designing parameter value is shown in *Table 1* [7].

Table 1 - Facility evacuation capacity

Facilities	Maximum capacity (person/(min·m))	Maximum velocity (m/min)
Walkway	81.9	37.8
		(Low density zone) 61.0
Stairway	55.5	14.63 (vertical)

2.3 "*Guideline*" of Taiwan MRT

The provisions about emergency evacuation of "*Guideline*" of Taiwan MRT are similar to the "*Standard*", but for the occupant load and facility evacuation capacity, it is more detailed, shown as follows:

$$W_1 = \frac{2IL.Lor1900 + 6F_1 + IF_2}{70(a-1) + 35b} \leq 4\,\text{min} \quad (4)$$

where F_1 - refers to peak minute passenger volume of peak direction; F_2 - peak minute passenger volume of off-peak direction; a - number of escalators ($a-1$

denotes one that is considered as having failed); *b* - number of equivalent 0.55m width stairways; *I* - is headway, min; *L.L* - section load, or line load; 1900 - passenger load of a fully loaded train (6-car train).

The platform evacuation load adopts the sum of the larger value between the crush load of a train and section load in two headways and the entraining passengers in 6 minutes of peak direction and that of off-peak direction in a headway.

For the calculation of the evacuation time of the most remote point, it is the same as the one in the "*Standard*".

2.4 Analysis of the main differences

In conclusion, the main differences of the provisions given by the three standards are presented respectively as follows:

(1) For the basic requirements of evacuation, the "Code" merely requires that pedestrians on the platform be evacuated in 5 minutes, while the "Standard" and the "Guideline" require that this should be completed in 4 minutes, and the total evacuation time from the most remote point to the safe point, which is not necessarily the concourse level, should be limited within 6 minutes. Actually, it is possible to have the pedestrians on the platform evacuated in 4 minutes, but the last pedestrian's total walking time may not be able to meet the requirement. For this problem, the "Code" regulates that the distance between any point on the platform and the exit of the stairs and escalators should be no more than 50 meters, which enables the time of walking on the platform less than the time waiting at the exit. Furthermore, according to the practical design of stations in China, although the concourse level and the platform belong to the same fire compartment, owing to the paid area which is divided by removable barrier the fare collection equipment is no longer the bottleneck in case of emergency, and as a result, the concourse level can be considered as a safe point. However, the walking time between the exits of the stairs/escalators and the concourse level may have effect on the last passenger, and this still needs further analysis whether such walking time should be calculated in the whole evacuation time.

(2) With regard to the calculation of the evacuation load on the platform, the "Code" considers just the crush load of a train, staff of the station and the passengers awaiting on the platform, where the exact volume of waiting passengers is not specified, while the designing staff adopts the number of waiting passengers of a headway. The "Standard" gives no definite calculation method of the passengers waiting on the platform, but the cases of delay and system response need to be taken into consideration. The "Guideline" presents the definite and conservative rules. The passengers waiting on the platform are divided into two groups: peak direction and off-peak direction. As to the peak direction, passengers waiting on the platform should be counted as passengers gathered in 6 minutes rather than one headway. The lager one between the section load in two headways and the crush load of a train is taken as evacuation load in train. Considering the reaction ability of the FAS system, it is practicable to take the entraining load in one headway. Since the current long-term headway of new lines in central areas is 2 minutes or even shorter, it may happen that two trains in opposite directions arrive at the same time during emergency events, and if the section load is larger than the crush load of a train, the calculation occupant load in the "Code" cannot meet the requirement.

(3) With respect to the evacuation capacity, the "Code" adopts the normal operation capacity of the stairs and escalators, while the "Standard" and the "Guideline" take escalators as stairways in case of emergency, and the value is less than that of the "Code" (upward-moving stairs capacity is 10.5 percent less than that of the "Code"). The provisions of the "Code" explain that because the evacuation capacity of the stairs is far less than that of the escalators, if the escalators are regarded as stairways in case of emergency, the scale and also the construction cost of the station will be much increased. As a solution, the electricity load of the escalators is raised to the first grade to guarantee normal operation in case of emergency. The "Standard" clearly specifies that the escalator out of service is assumed to be the most adverse to evacuation, but the "Code" gives no such specifications. The practical evacuation capacity cannot be experimented, so the maximum value in operation is adopted.

3. EVALUATION OF EVACUATION METHODS THROUGH SIMULATION

The analysis above indicates that compared with the standards of emergency evacuation in other countries and regions, the "Code" requires further study in parameter selection and evacuation time calculation method. The field experiments are unavailable for evaluating the evacuation method, while computer simulation provides a feasible way and it has been adopted in this paper to test and evaluate the evacuation method.

3.1 Case station and simulation model

A certain station in planning has been chosen as the case station: 6-car train, centre platform with single column, the peak hour factor is 1.3 and the future headway is 2 minutes. The basic data of pedestrians are as follows: the platform width is 13 meters, 3 meters for waiting areas on each side, two groups of stairs are settled splayed symmetrically, each side contains a group of escalators including an upward-moving and a downward-moving one, and the stairs in the middle of two escalators with a width of 2.5 meters. The facilities on the platform are settled as Feature 1. The section load denotes the passenger volume on the train just before arriving at the station.

Table 2 - Station forecast long-term passenger volume

Track	Long-term peak hour passenger volume (person/h)		
	Boarding passengers	Alighting passengers	Section load
Right	9,784	4,053	28,348
Left	8,753	6,839	26,816

Since the temporary barrier between the paid zone and the un-paid zone on the concourse level can be removed quickly, and a well designed ventilation system is designated, so it is reasonable to take the concourse level as a safe place and thus as the evacuation destination in the simulation analysis. In accordance with the passenger flow and facilities scale, using the calculation method and parameters in the “Code”, the evacuation time of the platform is 3.19min. (excluding 1 minute reaction time) and it meets the requirement. If using the practical capacity, the emptying time is 4.09min. and still the requirement is met. The time of 4.09 minutes is adopted as the value in the “Code”.

However, the calculation in the “Code” is based on a simple static volume-capacity method, while emergency evacuation is a complex dynamic process. Whether the above result is reliable, it is not certain. And also, according to Chapter 2, the method in the “Code” differs a lot from the one in design manuals of other countries or regions. To this end, it is necessary to apply micro-pedestrian simulation to evaluate the method and determine the reasonable one.

Thus, a 3D simulation environment of the case station has been built according to *Figure 1* with simula-

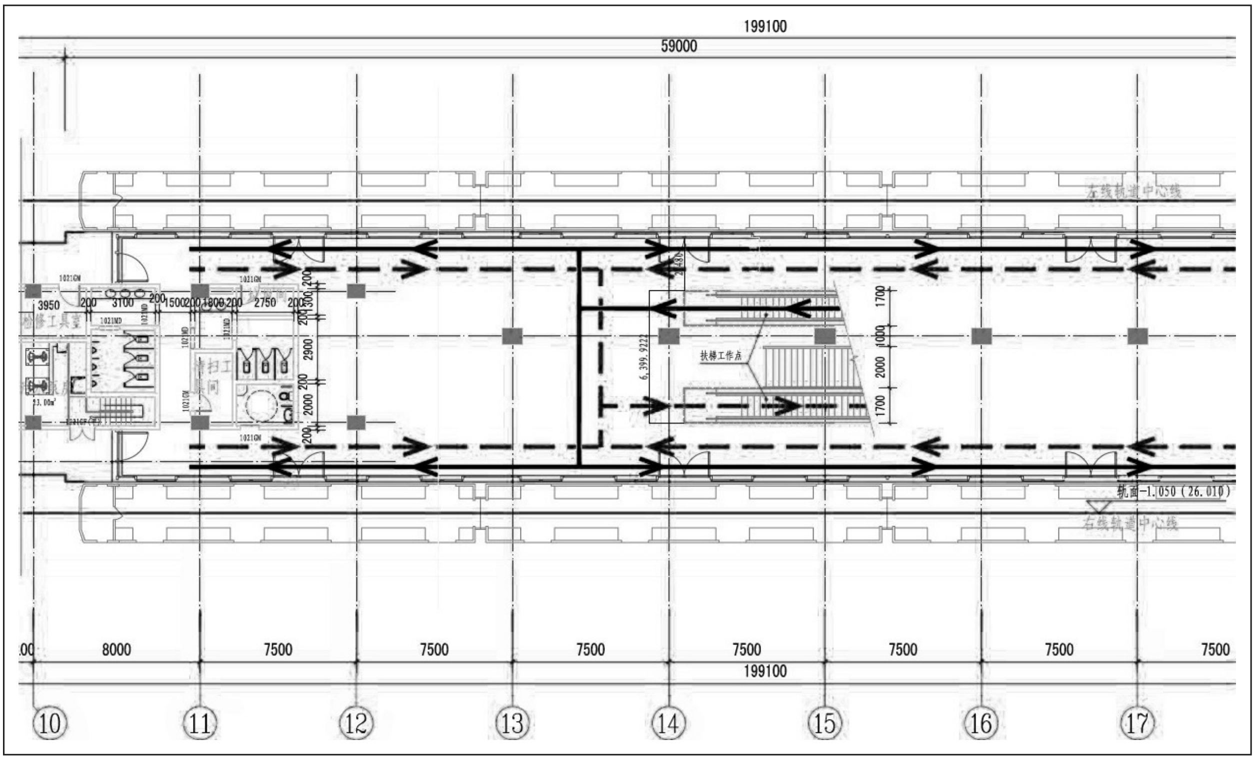

Figure 1 - Platform arrangement

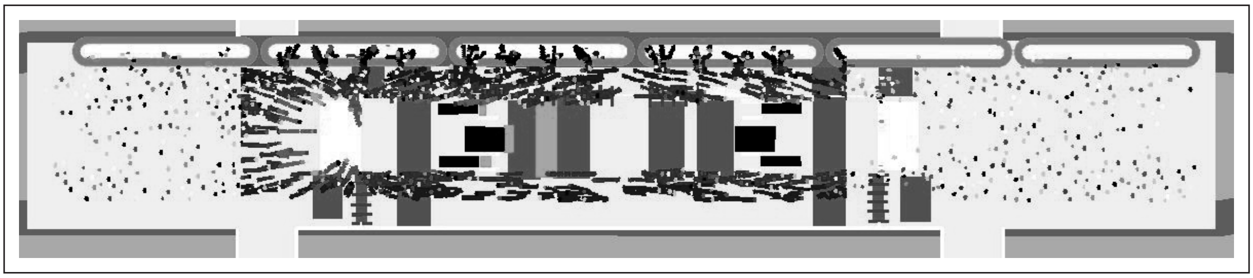

Figure 2 - Simulation model

tion tools developed based on the social force model [8-10], as shown in *Figure 2*, including the train.

3.2 Parameter calibration

According to abundant statistical data collected from the field study in typical urban railway stations in Beijing, the desired speed distribution of pedestrians on the stairs and the platform and the practical capacity of the stairs and escalators have been finally determined. The simulation model parameters were calibrated.

According to the features of pedestrian distribution on the steps, the practical capacity of the stairs and escalators cannot reach the design capacity. After calibrating the parameters including speed distribution etc. of the simulation model, the values of the maximum capacity obtained from the simulation are in accordance with the test results, which confirmed the rationality of the calibrated parameters.

Table 3 - Desired speed attained in stations from field study

Facility	Global		Stairway up (Horizontal Direction)	Stairway down (Horizontal Direction)
	Male	Female		
Max (m/s)	1.956	1.733	1.194	1.236
Min (m/s)	0.828	0.697	0.306	0.547
Mean (m/s)	1.391	1.180	0.700	0.728
Sq. Dev.	0.038	0.031	0.024	0.026

Table 4 - Facility capacity attained in practice from field study

Facility		Design manual (person/(min·m))	Practical (person/(min·m))
Escalator	0.65m/s	≤160	115
Stairways	Up	62	57
	Down	70	66

3.3 Scenario setting

There are five evacuation scenarios considered in the simulation based on the analysis in Chapter 2.

Scenario 1: The evacuation load in the “Code” includes entraining passengers awaiting trains for both directions in one headway (2 minutes here), which are 9,784/60×2×1.3=424 (rounded up) and 8,753/60×2×1.3=380 (rounded up) calculated from the long-term peak hour boarding passenger volume in *Table 2* with peak hour factor of 1.3, respectively, and crush load of one 6-B-type-car-train, which is 1,460 in design manual, and crew on the platform (15 persons). Then, the evacuation load in this scenario is totalized as 424+380+1,460+15=2,279. In addition, the most critical escalator for evacuation is considered out of service.

Scenario 2: Assuming that two trains arrive with train load of one headway on all tracks, the larger of the total train load and crush load of one train is adopted. In this case, the train load is 28,348/60×2×1.3 (rounded up) plus 26,816/60×2×1.3 (rounded up) derived from the long-term peak hour section load in *Table 2* with peak hour factor, which is bigger than the crush load of one 6-B-type-car-train, so it is taken as evacuation load in train. Entraining load and crew load is the same as in Scenario 1. Therefore, the evacuation load in this scenario is totalized as 424+380+1,229+1,163+15=3,211. The most critical escalator is considered out of service. Other conditions remain the same as in the “Code”.

Scenario 3: Similar to Scenario 1, whereas escalators are taken as stairways, with the most critical escalator out of service.

Scenario 4: Similar to Scenario 2, whereas escalators are taken as stairways, with the most critical escalator out of service.

Scenario 5: Similar to Scenario 1, with the least critical escalator out of service.

3.4 Analysis of simulation results

With the simulation model above, the five evacuation scenarios were carried out. The evacuation begins when the train arrives with the awaiting crowd randomly generated on the platform. According to the investigation, the model assumes that 80 percent of the crowd stands at both sides of the waiting areas and the rest of 20 percent in the middle circulation area facing the stairways. According to the research by Cheung [11], the probability of choosing escalator for passengers at the entrance of one abreast escalator-stairway and the time difference between using escalator and stairway fits Logistic regression. During simulation, the average time difference between 10 passengers traversing escalator and stairway is calculated dynamically, so the probability for the following passengers choosing escalator can be drawn through the Logistic model with calibrated parameters. According to the passenger flow ratio through the entrance and exit, the largest passenger flow volume emerges at the upward direction on the left platform with the adjacent and the farthest stairway and escalator being the most adverse and the most favorable conditions, respectively. The evacuation is completed when the pedestrians reach the concourse level area.

When the simulation ends, the walking time and the distance for each passenger were recorded. Then the total evacuation time and the average walking distance and time were calculated and listed in *Table 5*.

Figure 3 - Emergency evacuation begins when the train arrives at the station

Table 5 - Simulation results of evacuation simulation

Scenario	Total evacuation time(s)	Average evacuation time(s)	Average evacuation distance(m)	Compared with the calculation in the "Code" (s)	Whether with satisfaction
1	331	146	48.04	+86	Yes[1]
2	457	167	45.87	+212	No
3	448	209	47.55	+203	No
4	592	247	46.30	+347	No
5	299	119	46.34	54	Yes

Note 1: The requirement cannot be satisfied if the reaction time (1min.) is taken into account in practice.

The simulation results demonstrate the following:

1) Scenario 1 shows that, without counting the reaction time, the evacuation time in the simulation is 86s larger than the calculated time The main reason is that the alighting time of a person in the train loaded with passengers and the time spent on the stairway and escalator by the last pedestrian are not reflected in the calculation method. According to the simulation analysis of the travel time, the passenger alighting time is 11s; the average time of passengers to get through the stairway is 48s; the total is 59s. Therefore, they should be included in the calculation of the platform evacuation time.
2) Scenario 2 illustrates that, for stations with high section load as the case station, if the trains in opposite directions reach the station at the same time when the accident happens (which is highly possible), the occupant load will far outweigh the load calculated with the method in the “Code” (more than 40.90 percent), the corresponding evacuation time is 212s larger than the one calculated with the method in the “Code”, which is far from meeting the evacuation requirements.
3) Escalators are taken as stairways in Scenarios 3 and 4, with other conditions as Scenarios 1 and 2, respectively. The simulation results indicate that the evacuation times in the two scenarios increase by 117s and 135s, respectively where escalators are taken as stairways. To meet the requirement when the escalator is seen as stairways, the additional stairway must be provided and the station width and the construction cost will increase sharply. In fact, after upgrading the reliability from the secondary to the first grade, the failure rate of the escalators can be guaranteed. Therefore, it is not appropriate to be too conservative and to increase the investment dramatically.
4) Scenario 5 shows that the failure of the least or the most critical escalator has notable influence on the evacuation. In this case, the evacuation for the scenario with the least critical escalator hav-

ing failure takes 32s less than that for the scenario with the most critical escalator having failure. So it should be clearly specified that the evacuation time should be calculated in accordance with the condition where the most critical escalator is out of service.

4. CONCLUSION

Through comparative analysis of the typical evacuation test methods for rail transit stations in China and other countries, combined with field data and pedestrian simulation, the following main conclusions have been reached:

1) Through the comparison and analysis between the "Code" and the test methods of emergency evacuation in other countries and regions, the differences below can be confirmed: other standards consider not only the platform evacuation time, but also the walking time from the farthest point to the safe position; other standards consider evacuees load calculation in a more conservative and comprehensive way; although escalators are regarded as evacuation facilities in other standards, they are seen as the stairways, where the escalator most critical to evacuation should be assumed as having failed; the stairways and the escalators carrying capacities set in the "Code" are higher than those in other standards, but the actual values cannot reach the specified values.
2) The simulation illustrates that it takes more time to egress than the time that was calculated. The main reason is that the time of passenger's alighting and passing through from the escalator to the platform is not reflected in the calculated value.
3) For the stations with high section load, when two trains on both tracks reach the station simultaneously, the evacuation time is much longer than the scenarios where there is only one fully loaded train.
4) When the evacuation is calculated, the position of the failed escalator has a great influence on the evacuation time.

Based on the conclusions above, the test method in China can be improved in the following aspects:

1) Because many of the paid and free areas of the concourse level are temporary barrier the concourse level has high egress capacity. In addition to the well-designed FAS and ventilation system, the concourse level can be regarded as safe area as specified in "Code" [12], but the walking time on the stairways and the escalators should be included into the platform evacuation time.
2) The evacuation load shall adopt the larger one between the crush load of a train and the section load, and should also include the entraining load and the staff.
3) The escalator with most adverse effect on evacuation should be assumed as having failed.
4) As the facility evacuation capability adopts the measured value, while other values remain the same, the calculation formula is as follows:

$$T = 1 + \frac{\max[Q_v,(IQ_l)] + IQ_b + Q_s}{0.9[A_1(N-1) + A_2B]} + T_s \quad (5)$$

where, Q_v denotes full passenger volume in a train; Q_l, section passenger volume; Q_b, the number of waiting passengers; Q_s, the working staff; I, headway; T_s, walking time from the platform to the concourse level, and the meanings of other parameters are the same as in Formula 1.

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Ō城市轨道交通车站紧急疏散检算方法对比分析与仿真评价

摘 要

轨道交通车站紧急疏散检算方法不仅关系到车站的运营安全，同时对车站规模和造价有重要影响。合理的检算方法应该能在保证乘客疏散安全的同时不至投入过大，过于保守。本文比较分析了目前国内外设计规范中检算方法在人员疏散负荷、疏散时间计算和通过能力取值等方面的异同。采用调研分析的方法确定了行人速度分布和设施通过能力，标定了计算机仿真工具的参数，并选择案例车站建立了行人疏散仿真模型，根据不同规范的差异设定了5个仿真疏散工况，并对仿真结果进行了深入分析，基于此提出了考虑断面客流量、计入楼扶梯行走时间和明确故障扶梯应为最不利位置的扶梯等紧急疏散方法改进建议。

关键词

城市轨道交通车站 紧急疏散比较 行人仿真

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