**Effect of carriage interior design on passenger evacuation, boarding and alighting efficiency**

**Abstract**

This paper examines the effect of carriage interior design on the evacuation, boarding and alighting of passengers through experiments and simulations. Passenger movement speed is defined via a real-life scenario model of the carriage, and the extreme scenario is simulated using pedestrian traffic simulation software. A 7-factor mixed-level orthogonal experiment for the geometric characteristics of carriage design was established. The results of range analysis show that the effect of design factors on evacuation, boarding and alighting time is not entirely consistent, and seat layout and door width are of greatest importance. The degree of influence of all factors was tested via analysis of variance. In the evacuation scenario, only the influence of carriage connectivity is not significant. Seat layout, vehicle type, door width and foyer width have a significant impact on boarding and alighting time. A new scheme is proposed that achieves better performance.

Keywords: carriage layout, evacuation, boarding and alighting, simulation experiment

**1. Introduction**

Urban rail is the most crowded form of public transportation. In Europe and Australia, 4 passengers per square meter is a common level of crowding [1]. In the United States, this figure is 5 pass/m2 [2]. In developing countries, subways are even more crowded. China has adopted a density of 6 pass/m2 as a design standard [3], while India observes limit situations of 14–16 pass/m2 [4]. According to statistics for 2020, China has the heaviest urban rail transit passenger flow; the passenger flow of the top 10 cities all exceed the world average [5]. The most direct problem caused by congestion the movement of people in rail cars [6, 7].

Boarding and alighting is the most basic scenario in passenger use of rail transportation. If already built lines want to increase service frequency by reducing train dwell time, it is necessary to shorten the waiting time of passengers on platforms and in cars [8]. The higher the efficiency of boarding and alighting, the better the optimization of train organization and operation [9]. Interior layout is the key factor affecting boarding and alighting [10]. Importantly, the efficiency of the movement of people in the car is closely related to passenger evacuation in emergency situations. Many accidents have shown that the inability to evacuate the carriage within a limited time may lead to devastating consequences, such as the 289 deaths in the Azerbaijan metro fire of 1995 [11] and the 192 deaths in the Daegu subway fire in 2003 [12]. Most subway evacuation studies use fire as the main factor in accident simulation. The literature mainly discusses such variables as smoke concentration [13], heat release rate [14] and ignition point [15]. However, in almost all train emergencies, including power failures, terrorist attacks, flooding and earthquakes, evacuating passengers is the primary task. Even if it is not considered in the evacuation scenario, 26.67% of injuries or stampede accidents are caused by overcrowded carriage boarding and alighting [16].

A number of studies show that reasonable carriage design plays an important role in improving passenger flow [17–20]. Previous studies focus on the effect of carriage design on evacuation, and few studies link carriage design with boarding and alighting. First, these studies focus on the key factors that affect passenger flow, such as doors and aisles, but ignore other geometric variables. Second, although factors affecting passenger flow are examined, there is a lack of focus on the degree of influence of these factors. Finally, the two behaviors of evacuation and boarding and alighting are always studied separately. In our view, the geometric characteristics of the carriage have the same mechanism of effect on both evacuation and boarding and alighting of passengers. Therefore, the present study uses the same interior design variables in evacuation and boarding and alighting experiments. Our purpose is: 1) to study whether the influence of design factors on evacuation and boarding and alighting is consistent; 2) to examine the degree of influence of each factor; 3) to apploy the results to guide train design.

**2. Literature review**

Many scholars have studied the impact of built structures on the flow of people, most commonly subway stations [21] and tunnels [22]. Some studies focus on the variables that affect flow efficiency inside buses [23], civil aircraft [24], ordinary trains [20] and high-speed trains [19], but only a few address subway trains. First, we review the design factors in the literature that affect the evacuation, boarding and alighting of passengers, with the aim of identifying experimental variables applicable to subway carriages. Then, the existing research methods are reviewed, the most common real-life experiment and simulation methods are compared, and our experiment is designed to take into account efficiency, safety and effectiveness.

**2.1. Influencing variables**

Many factors affect passenger evacuation and boarding and alighting time. These can be summarized as factors outside the carriages, factors regarding passengers and attendants, and factors inside carriages. Factors outside the carriage include station design [25], the platform screen door (PSD) [26], the vertical height difference between the train and the platform [10] and the horizontal gap [18, 27]. In an emergency evacuation scenario in which the station cannot be reached, the train gangway [20], tunnel exit [28], etc. are considered. Human behavior is also a key factor causing time differences, such as the competition and compromise behavior of passengers during boarding and alighting, as well as emergency behavior of passengers and train attendants. For the interior design of the carriage, Seriani and Fernandez [33] study the influence of the position of the foyer handrail on boarding and alighting, a very important contribution. Costa Neto and Santos [34] argue that average time needed for passengers to board and alight in any subway car is affected by the total width of the exit (number of doors multiplied by door width). Thoreau et al. [18] observe in the laboratory that the impact of carriage design on boarding and alighting depends on the number of passengers. When the number of people boarding and alighting is the same, doors with medium width (1.7 m) perform best. When most people are alighting, the widest door (1.8 m) performs worst. When most people are boarding, the wider the door, the better, but there is no difference between a door width of 1.7 m and 1.8 m. This indicates that the benefit of increasing door width is weakening. Fujiyama et al. [35] find that increasing the width of the carriage foyer is conducive to passenger flow, but does not bring substantial changes after a particular threshold is exceeded. According to Qiu and Fang [19], only changing the aisle of the carriage or width of the door does not affect evacuation time. However, increasing the distance between the front and rear seats can promote or ​inhibit evacuation, which depends on interaction with aisle width. Studies on the effects of internal factors on passenger flow are shown in Table 1.

Table 1. Main literature on the impact of interior design on passenger flow

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Author | Research object | Variables | Method | Main conclusions |
| Seriani and Fernandez [33] | Subway train | Position of the pole | LEGION simulation combined with real-life experiments | A pole close to the door frame performs better than a pole in the center of the foyer. It is best is to set the pole in the middle of the door frame. |
| Costa Neto and Santos [34] | Subway train | Carriages with three doors or four doors, central pole | Real-life experiment on model carriages | It takes less time to board and alight in a four-door carriage than in a three-door carriage, and which installed the central pole will take 13% more time. |
| Thoreau et al. [18] | Subway train | Door width, center pole, seat type, standback | Real-life experiment on model carriages | Door width of 1700–1800 mm is best; other factors have no obvious effect on boarding and alighting. |
| Fujiyama et al. [35] | Subway train | Door width | Real-life experiment on model carriages | 1800 mm door shows greatest improvement in flow rate. When the Standback exceeds 400 mm, flow rate will not continue to increase. |
| Fridolf et al. [20] | Ordinary train | Light intensity | Real-life experiment on model carriages | When there is no lighting in the train, the decrease in the speed of flow of people is significant. |
| Yu et al. [36] | Ordinary train | Number and location of open doors | Real-life experiment combined with EXODUS for simulation | It is faster to evacuate by ​opening two doors on one side of the carriage than opening one door on each side of the carriage. |
| Qiu and Fang [19] | High-speed train | Aisle width, door width, seat pitch | Simulation using Legion | Only the main effect of seat pitch is significant; the main effect of door width and aisle width is not significant. |
| Wang et al. [37] | High-speed train | Door width, hall width, aisle width | Simulation using Legion | Door width of 1300–1400mm shows best performance; wider halls and aisles correspond to higher boarding and alighting efficiency. |
| Schelenz et al. [23] | Bus | Carriages with three doors or four doors | Simulation using ANYLOGIC | Compared with three-door carriage, four-door carriage helps to redistribute the passenger flow of the middle door. |

**2.2. Research methods and evaluation indicators**

The above-described literature shows that real-life testing and computer simulation are the most commonly used methods to study passenger flow. Real-life testing can truly uncover the behavior of passengers in the process of evacuation and boarding and alighting [19], but this method comes at high experimental cost. Therefore, Fridolf et al. [20], Costa Neto et al. [34] and Daamen et al. [10] used partly carriage models instead of panoramic experiments and proved that the experimental method of scenario simplification is effective. When there are many scenarios to be tested in the real-life experiment, considering factors such as scenario replacement and reduced subject physical fitness, the cycle and cost of the experiment are difficult to control, and more importantly, the real-life experiment has unpredictable safety risks. Computer simulation has clear advantages in safety, experiment speed and operating cost. A micro pedestrian model describes and calculates the behavior of each person independently. It can not only simulate pedestrian traffic flow from a macro level, but also describe the complex behavior of pedestrian traffic in detail [38]. The most typical such models are the cellular automata model (CA), social force model (SFM) and agent-based model (ABM). These simulation models are maturely used in commercial pedestrian traffic simulation software such as LEGION, ANYLOGIC, EXODUS and PATHFINDER. It is confirmed that there is little difference between the models and real-life experiments [19]. The PATHFINDER simulation software used here was developed by Thunderhead Engineering based on ABM. PATHFINDER has been widely used in pedestrian simulation of rail transit stations [41]. This software shows excellent performance in cabin evacuation simulation of civil aircraft [42, 43], which is very similar to the environment of train carriages.

Flow (passengers/second or passengers/second meter) and time are the commonly used indicators to measure efficiency of passenger flow. At the micro level, calculating the flow of a single door is very helpful in analyzing passenger selection. However, when measuring overall efficiency, there is no difference between using the average flow of all doors and using the total time. In China’s national standards, there is no mandatory time for boarding and alighting. Safe evacuation time available for train and platform passengers cannot exceed 6 minutes [44], which is judged using total time. We focus mainly on the effect of interior design of the carriage on the efficiency of evacuation and boarding and alighting, and compare differences caused by different design parameters. Time is considered to be a more intuitive basis for judgment.

**3. Methods**

An orthogonal experimental design of a subway carriage with different design parameters was established, and evacuation and boarding and alighting scenarios were simulated via simulation method. Before the formal experiment, a pre-experiment was carried out, because we need to know what passenger walking speed to use in the simulation to ensure authenticity of the results.

**3.1 Passenger walking speed**

Passenger walking speed is the basis of crowd flow. A train evacuation experiment conducted by the United States Federal Railway Administration (FRA) in Boston shows that average speed for men is 1.5 m/s and for women it is 1.3 m/s [45]. Yu et al. [36] concludes that a walking speed of 1.0–1.2 m/s is more reasonable in evacuation simulations for ​Chinese trains. According to Luangboriboon et al. [6], passengers face limited space when boarding, from low-density areas through doors to higher-density carriages, while there is unlimited space to face during evacuations. These scenarios may cause people to travel at different speeds during boarding, alighting and evacuation. Therefore, there are two main factors leading to different walking speeds. One is the sample structure: gender and the ratio of young and old [46]. The other is crowd density. Many studies test the effect of crowd density on walking speed in different scenarios. Their conclusions tend to be consistent. Higher crowd density corresponds to lower walking speed [47–49]. Based on the above-described literature, let us assume that the walking speed of adults in the riding behavior is in the range of 1.0–1.5 m/s. A preliminary experiment is designed to solve for walking speed when the time of the simulated scenario is consistent with that of the real-life scenario at a passenger density of 6 pass/m2.

The subway carriage can be simplified into two basic functional modules: the door area and the seating area (including the area in front of the seat). We built a real-life carriage for experimentation. It is one-third scale of a full-size Chinese wide-body carriage (type-A vehicle), including a complete set of functional modules, as shown in Figure 1.

Figure 1. Real car: (a) top view; (b) photo.

The preliminary experiment recruited 120 young people from Southwest Jiaotong University, including 38 males, with an average shoulder width of 42.7 cm, 42 females, with an average shoulder width of 40.2 cm. The subjects are between 21 and 28 years old and have experience in taking the subway. When all subjects enter the real-life car, the corresponding standing density in the car is 6 pass/m2, which is the maximum density of rated passenger capacity in the Chinese subway standard [3]. The ground area where subjects are not allowed to stand is marked with yellow tape. As this work focuses mainly on the impact of carriage interior design on evacuation and boarding and alighting, it is necessary to reduce the interference of other factors as much as possible. These include carriage height, gangway, platform gap, and disabled groups. Only the two most common extreme scenarios are considered: 1) fully open door to evacuate to the platforms on both sides under full load; 2) with door open on one side, 50% of passengers alight and the same number of passengers board. The two scenarios of the pre-experiment are shown in Table 2.

Table 2. Scenario setting of pre-experiment

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | Passenger behavior | Door status | Initial number of people in the carriage | Number of people boarding | Number of people alighting | Number of people stranded in the carriage | Total number of participants |
| 1 | Evacuation | Bilateral opening | 80 | 0 | 80 | 0 | 80 |
| 2 | Boarding and alighting | Unilateral opening | 80 | 40 | 40 | 40 | 120 |

The experimental intention and precautions were explained to all subjects before the experiment. The evacuation scenario requires the subjects to leave the carriage as soon as possible, while the subjects in the boarding and alighting scenario are randomly divided into a boarding group, an alighting group and a stranded group. To reduce error caused by fatigue, the experiment was carried out over two days. The evacuation experiment was carried out on the first day (Figure 2 (a)), and the boarding and alighting experiment was carried out on the second day (Figure 2 (b)). Both scenarios were tested 10 times, with a five-minute interval. A dedicated experimenter reports the ‘start’ and counts the time until the last subject passes through the door. This period of time is used as an experimental output.

Figure 2. Experiments in real-life carriage: (a) evacuation; (b) boarding and alighting.

Correspondingly, a digital model identical to the real-life carriage was established in PATHFINDER, and the gender ratio and average shoulder width of the subjects were set in accordance with the participants in the experiment. Walking speeds of 1.0 and 1.5 m/s were used, respectively, to complete the experiments in the boarding and alighting and evacuation scenarios. Similarly, each simulation scenario was run 10 times, and the positions of the subjects were rearranged randomly each time. The simulated scenario is shown in Figure 3.

Figure 3. Simulation experiment: (a) evacuation; (b) boarding and alighting. Notes: Red, yellow and blue circles indicate, respectively, people boarding, alighting and remaining, and the arrows indicate direction of movement.

The output time obtained in the real-life carriage experiment is compared with the output time obtained by simulation under different walking speeds, and the independent sample t-test is used. The experimental results of the two scenarios are shown in Table 3 and Table 4.

Table 3. Results of the independent sample t-test in the evacuation scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Comparison item | Walking speed (m/s) | *t* | P-value | Mean difference (s) |
| Time required for real-life experiment vs. simulation experiment | 1.0 | –107.500 | <0.001 | –7.17 |
| 1.1 | –13.761 | <0.001 | –6.03 |
| 1.2 | –52.000 | <0.001 | –3.47 |
| 1.3 | –24.684 | <0.001 | –2.97 |
| 1.4 | 0.500 | **0.643** | 0.03 |
| 1.5 | 5.000 | 0.007 | 0.33 |

Table 4. Results of independent sample t-test in boarding and alighting scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Comparison item | Walking speed (m/s) | *t* | P-value | Mean difference (s) |
| Time required for real-life experiment vs. simulation experiment | 1.0 | –25.458 | <0.001 | –2.33 |
| 1.1 | –9.177 | 0.001 | –1.33 |
| 1.2 | –0.359 | **0.738** | –0.03 |
| 1.3 | 6.325 | 0.03 | 0.67 |
| 1.4 | 20.555 | <0.001 | 2.167 |
| 1.5 | 16.977 | <0.001 | 2.47 |

In the evacuation scenario, when the walking speed is 1.4 m/s, there is no significant difference in time between the two sets of experiments (*p* > 0.05), so it is reasonable to set an average walking speed of 1.4 m/s in the simulation experiment for train evacuation. Similarly, in the boarding and alighting scenario, when the walking speed is 1.2 m/s, there is no significant difference in time between the two groups of experiments (*p* > 0.05), indicating that an average walking speed of 1.2 m /s can be used to simulate passenger boarding and alighting.

**3.2. Scenario setting for formal experiment**

The scenario setting of the formal simulation experiment is the same as that in Section 3.1. The number of people to be added in the experiment was calculated according to the maximum density of 6 pass/m2, because changes in design features of the carriages will lead to differences in the standing area. If the experiment were carried out with the same number of people, this would produce varying standing density, affecting walking speed [47]. The formal experiment uses three complete carriage marshalling models. Males and females each account for 50% of passengers, and the maximum shoulder widths of males and females at the 50th percentile are set according to data from the China adult body size standard [50]. Each time the simulation is completed, the positions of the participants are rearranged randomly.

**3.3 Experimental variables**

Considering Section 2.1 and the actual situation of the vehicle being used, this paper takes vehicle type (A), door symmetry (B), carriage connection (C), door width (D), foyer width (E), seat (F) and pole layout (G) as the independent variables. Figure 4 is a schematic diagram of the independent variables and does not represent the real ​carriage design. Time is a dependent variable.

Figure 4. Schematic diagram of variables: (a) narrow carriage; (b) wide carriage

* Vehicle type (A): Narrow carriage (type-B vehicle) and wide carriage (type-A vehicle) are the two most widespread types in China. Almost all existing carriages are developed based on these two types. Their main difference is that the wide carriage has an extra set of functional modules, that is, the wide carriage has five pairs of doors, while the narrow carriage has only four pairs of doors.
* Door symmetry (B): Although the vast majority of carriage designs are symmetrical along the central axis, asymmetrical designs are also in use. For example, the R-142 and R-32 models in the New York subway (built by Bombardier Transportation) [51] use asymmetrical doors. Accordingly, the layout of seats is also asymmetric. In this setting, only one-third of the door width is coincident.
* Carriage connection (C): Whether passage is allowed between carriages. For example, the 05C01 model 4 marshalled train (Built by Alstom Transport) on Shanghai Metro Line 5 does not allow passengers to pass through the connections of the carriages.
* Door width (D): Effective width of the door that allows passengers to pass through. This variable includes the minimum width specified by the national standard of 1300 mm [3], the most common width of 1400 mm for wide vehicles, and a maximum width of 1500 mm.
* Foyer width (E): Width between left and right seat baffles after entering through the door.
* Seat (F): Includes the most basic longitudinal and transverse seat layouts, as well as four mixed layouts. For the same vehicle type, the number of seats is unchanged.
* Pole (G): Arrangement of vertical poles on the central axis of the carriage.

The geometric dimensions of the above variables, including seat size, pole diameter and size of the space at the connection of the carriage, are consistent with vehicles in operation. The factors and levels of the experiment are shown in Table 5:

Table 5. Experimental factors and levels

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Levels | A | B | C | D | E | F | G |
| Model | Door symmetry | Carriage connection | Door width (mm) | Foyer width (mm) | Seat | Pole |
| 1 | Narrow vehicle | Symmetric | Connected | 1300 | 1650 | Longitudinal seat | Without pole |
| 2 | Wide vehicle | Asymmetric | Disconnected | 1400 | 1850 | Longitudinal seats only at both ends | One pole in front of seat |
| 3 | — | — | — | 1500 | 2050 | Transverse and longitudinal alternating seats (opposite and side of longitudinal seats are transverse seats) | One pole in center of door area |
| 4 | — | — | — | — | — | Transverse seats only at both ends | Two poles in front of seat |
| 5 | — | — | — | — | — | Only left side at ‘B’ end of car and right side at ‘A’ end of car are longitudinal seats. | A pole in each door area and in front of seat. |
| 6 | — | — | — | — | — | Transverse seats | Two are in front of the seats and one is in the door area. |

**3.4. Experimental design**

A full factor experiment of 7 factors will yield 23×32×62 = 2592 test schemes. Clearly, this amount of experiments is too large. Because the participants in each simulation are rearranged, there are random errors, so a full factor experiment is unnecessary. Only a typical combination of each factor level needs to be tested. We establish a mixed-level orthogonal experiment: L36 (23×32×62), yielding only 36 schemes to test. We run 10 simulations for each scenario to reduce errors. The experimental scheme design and mean value of the results are shown in Table 6.

Table 6. Orthogonal experimental design.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test number | A | B | C | D | E | F | G | Average evacuation time(s) | Average boarding and alighting time(s) |

**3.5. Data processing**

First, a range analysis is carried out to obtain the primary and secondary order of the influence of various factors on the time required for evacuation and boarding and alighting. Then, the significance of the factors on time was confirmed by analysis of variance (ANOVA) using the data from each simulation instead of the average value of the scenario; the LSD method is used for post-hoc comparison. Alpha levels are considered significant at 0.05 and very significant at 0.01.

**4. Results**

A range analysis of output time is performed, and the results are shown in Table 7.

Table 7. Range analysis results

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Index | A | B | C | D | E | F | G |
| *Ke*1 |  |  |  |  |  |  |  |
| *Ke*2 |  |  |  |  |  |  |  |
| *Ke*3 |  |  |  |  |  |  |  |
| *Ke*4 |  |  |  |  |  |  |  |
| *Ke*5 |  |  |  |  |  |  |  |
| *Ke*6 |  |  |  |  |  |  |  |
| *Re* |  |  |  |  |  |  |  |
| *Kb*1 |  |  |  |  |  |  |  |
| *Kb*2 |  |  |  |  |  |  |  |
| *Kb*3 |  |  |  |  |  |  |  |
| *Kb*4 |  |  |  |  |  |  |  |
| *Kb*5 |  |  |  |  |  |  |  |
| *Kb*6 |  |  |  |  |  |  |  |
| *Rb* |  |  |  |  |  |  |  |

*Notes*: *Ke*is the average of the average evacuation time at the same level under each factor; *Kb* is the average value of the average boarding and alighting time at the same level under each factor; *Re* = *Ke*(max)−*Ke*(min); *Rb* = *Kb*(max)−*Kb*(min), and the *R* value indicates the degree of effect.

The results of the range analysis show that various factors have differing effects on evacuation and boarding and alighting time. For evacuation scenarios, the order of influence of the factors is: seat (F) > door width (D) > vehicle type (A) > pole (G) > foyer width (E) > door symmetry (B) > carriage connectivity (C). For boarding and alighting scenarios, the order of influence of the factors is: seat (F) > door width (D) > foyer width (E) > pole (G) > vehicle type (A) > carriage connectivity (C) > door symmetry (B). The level mean value of each factor is shown in Figure 5.

Figure 5. Mean value of the scheme at each level in the factors: (a) evacuation time; (b) boarding and alighting time.

The optimal combination of two range analyses can be obtained from Table 7 and Figure 5. For evacuation: A2B2C2D3E2F1G1; for boarding and alighting: A1B2C1D3E3F1G5. These two combinations are consistent only in the performance of the level of door symmetry (B2) and door width (D3). For other factors, the significance of the effect and the specific difference between levels need to be tested via ANOVA. Table 8 shows the ANOVA results.

Table 8. Inter-subject effect

|  |  |  |
| --- | --- | --- |
| Factor | Evacuation scenario | Boarding and alighting scenario |
| SS | df | F-value | P-value | SS | df | F-value | P-value |
| A | 369.81 | 1 | 294.23 | 0.000\*\* | 401.92 | 1 | 6.28 | 0.013\* |
| B | 44.79 | 1 | 35.66 | 0.000\*\* | 30.32 | 1 | 0.47 | 0.492 |
| C | 4.78 | 1 | 3.80 | 0.052 | 42.95 | 1 | 0.67 | 0.413 |
| D | 377.11 | 2 | 150.01 | 0.000\*\* | 1797.44 | 2 | 14.03 | 0.000\*\* |
| E | 44.82 | 2 | 17.82 | 0.000\*\* | 991.139 | 2 | 7.73 | 0.001\*\* |
| F | 378.42 | 5 | 60.22 | 0.000\*\* | 6450.08 | 5 | 20.14 | 0.000\*\* |
| G | 97.58 | 5 | 15.52 | 0.000\*\* | 413.14 | 5 | 1.29 | 0.268 |

*Notes*: \*represents significance at the level of 0.05; \*\*represents significance at the level of 0.01.

The ANOVA results show that the effect of vehicle type on evacuation (*p* < 0.001) and boarding and alighting (*p* = 0.013) is significant. Whether the doors are symmetrical only affects evacuation efficiency (*p* < 0.001) but will not affect boarding and alighting. Whether the carriage is connected has no significant effect on evacuation and boarding and alighting time.

The factors of df ≥ 2 are examined by post-hoc test. The results of pairwise comparison show that the difference of any door width is significant during evacuation (all *ps* < 0.05). In the boarding and alighting scenario, there is no significant difference between 1400 mm door and 1500 mm door, but the time is significantly less than 1300 mm door (all *ps* < 0.001).

For the foyer width, the design of 1850 mm performs best during evacuation, but there is no difference from the size of 2050 mm. The foyer of 1850 mm and 2050 mm takes less time than the foyer of 1650 mm (all *ps* < 0.001). There is no significant difference between the 1650 mm and 2050 mm foyers when boarding and alighting, while the foyer with a medium width of 1850 mm shows a significant disadvantage (all *ps* < 0.05).

The seat layout has a significant effect on time (all *ps* < 0.001). In both scenarios, all longitudinal seats take less time than other layouts (all *ps* < 0.001). Transverse and longitudinal alternating seats (level 3), transverse seats at both ends (level 2) and longitudinal seats at both ends (level 4). These three mixed layouts have no difference in the effect on evacuation and boarding and alighting time. However, the design with a set of longitudinal seats (level 5) at each end of the carriage takes the most time in evacuation scenarios (all *ps* < 0.001), more than the layout with all transverse seats (level 6) (*p* < 0.001). In the boarding and alighting scenario, there is no difference between level 5 and level 6, but it takes significantly more time than other layout methods (all *ps* < 0.05).

The effect of any pole arrangement on boarding and alighting is not significant. The evacuation time for not using the pole (level 1) and installing a pole (level 3) in the door area is the shortest, and the difference between the two is not significant. There is not much difference between using a single pole (level 2) or two poles (level 4) in front of the seat, but it takes more time than using a pole in the door area or not using a pole (all ps < 0.05). The layout of the poles (level 5 and level 6) in both the door area and in front of the seat is the most obstructive to evacuation, and there is no difference between level 5 and level 6.

**5. Discussion**

Reviewing the three objectives of the study, the ranking of the influence of design factors on time has been obtained through range analysis (objective 1), and the degree of influence of the factors has been further clarified through ANOVA (objective 2). However, the levels of some factors are not consistent in evacuation and boarding and alighting scenarios. This leads to neither of the two optimal solutions obtained from the range analysis can satisfy the minimum evacuation and boarding and alighting time at the same time. Therefore, further discussion is needed for guiding the train design (objective 3), especially to get a scheme with better comprehensive performance

**5.1. Effect of carriage design**

**5.1.1. Vehicle type**

The study compared narrow carriages with four pairs of doors and wide carriages with five pairs of doors. There is no consistent conclusion on which carriage performs better in evacuation and boarding and alighting. The wide vehicle is more conducive to the evacuation of passengers, because the number of doors increases, representing a larger width of the total exit, which is consistent with the conclusion of Yu et al. [36]. Wide vehicles also have wider aisles, and the increase in aisle width is considered by Qiu and Fang [19] as an auxiliary factor conducive to evacuation. On the other hand, narrow vehicles are more conducive to boarding and alighting. In theory, more doors should be more conducive to boarding and alighting [23, 34], we support this view. However, the wide carriages used in this study are longer than the narrow carriages (Figure 4). The distribution of 5 pairs of doors is not concentrated than that 4 pairs of doors. When one door is crowded, passengers will queue at another door, and the more dispersed doors affect the efficiency of getting on and off. For narrow vehicles, the activity space of passengers after boarding is limited, thus the time of passenger flow exchange is shortened. From these aspects, narrow vehicles are beneficial to boarding and alighting. The results of ANOVA showed that the effect of vehicle type on evacuation was more significant (*p* < 0.001), while the effect on boarding and alighting was only significant at the level of *α* = 0.05. Therefore, the use of wide vehicles is more encouraged, especially from the perspective of safety.

**5.1.2. Symmetrical doors**

Using asymmetric layouts is a novel design. The subway cars currently in service in China are symmetrical. However, considering the wide use of this design in New York and other cities, especially Bombardier Transportation, the manufacturer of these carriages, is also the main project supplier of CRRC. Therefore, it is necessary to explore the application prospect of asymmetric form from the perspective of passenger flow. It is found that whether symmetrical doors are used has no significant impact on boarding and alighting, only significantly affecting evacuation times (*p* < 0.001). As can be seen from Figure 5, asymmetrical doors perform better in both evacuation and boarding and alighting scenarios. Berkovich et al. [51] believes that the layout of symmetrical doors will make passengers to squeeze at the doorway and increase the load on the door area, which is discussed from the perspective of load utilization. This study complements the evidence in favor of passenger mobility.

**5.1.3. Carriage connection**

Whether the cars are connected or not has little effect on the evacuation and boarding and alighting time, which means that both designs are possible. This conclusion is drawn from the experimental scenario we defined. From other aspects, the connected carriages are more conducive to the evacuation of passengers to adjacent carriages in a fire [36], and of course, it may also contribute to the spread of the fire. The circulation of passengers among the carriages also helps to alleviate the congestion of individual carriages and improve the utilization rate of trains. In general, the benefits of using connected carriages are greater.

**5.1.4. Door width**

The width of the door plays a very important role in both evacuation and boarding and alighting (all *ps* < 0.001). The obvious conclusion is that the larger the door width, the more conducive for flow of people. Some argue that improvements in the efficiency of personnel flow will become more and more limited as exports increase to a certain width [52]. In the evacuation scenario, although the difference in the width of the three kinds of doors is statistically significant, it can be seen from the mean value graph (Figure 5) that the reduction of evacuation time becomes slower when it increases from 1400 mm to 1500 mm. This trend is more obvious in the boarding and alighting scenario. There is no difference in boarding and alighting time using 1400mm and 1500 mm doors. These conclusions are different from the phenomena observed by Qiu and Fang [19] in high-speed trains. Qiu and Fang [19] believe that the reduction in evacuation time is not only affected by the increase of door width, but also depends on whether the doorway is crowded. In high-speed trains, passengers are unlikely to crowd at the doorway, so the effect of door width on evacuation time is not significant. However, in subway cars, the study defines that passengers evacuate at crowded density, which leads to the important role of door width. The effect of door width on boarding and alighting efficiency is consistent with Fujiyama et al.'s [35] conclusion that wider doors can support more people streams. Therefore, it is recommended to install a door of at least 1400 mm.

**5.1.5. Width of the foyer**

Inconsistent results were obtained by changing the lobby width in evacuation and boarding and alighting scenarios. First, the increase in the width of the foyer does not correspond exactly to the decrease in time. In this study, the foyer with medium width (1850 mm) is the most controversial design. It performs best in evacuation but has obvious disadvantages in boarding and alighting. Parameters that are extremely unfavorable in any aspect will not be considered for use in the design. The 2050 mm foyer used in the evacuation is no different from the 1850 mm foyer, and 2050 mm foyer takes the least time in boarding and alighting. Therefore, the 2050 mm foyer has the best comprehensive performance. This is considered from the design parameters of active trains. Previous studies have also explained the nonlinear relationship between the influence of lobby width on flow of people from other angles [18]. Fujiyama et al. [35] believes that too wide foyer will cause passengers to stay near the screen, so the benefits of widening the lobby are not obvious. However, it is undeniable that the main effect of the width of the foyer on evacuation (*p* < 0.001) and boarding and alighting (*p* = 0.001) is significant.

**5.1.6. Seat layout**

The seat layout in almost all active subways is considered in the experiment. The layout of the longitudinal seat can provide more standing area during peak hours, so it is the most widely used. From the perspective of passenger flow, the longitudinal seat leaves the widest aisle, which is obvious to help evacuation and boarding and alighting. In recent years, many cities have begun to purchase mixed-layout carriages, which are used in non-busy lines. The number of seats provided by the mixed layout is no different from the longitudinal layout, but the evacuation and boarding and alighting efficiency is much lower than that of the longitudinal layout (all *ps* < 0.001). The longest time is the layouts of the transverse seats, and a set of longitudinal seats at each end of the carriage (level 5). In these two layouts, the number of transverse seats is significantly higher, resulting in the reduction in the width of available aisle, which affects the flow of people.

A special case in the evacuation scenario needs further discussion. The layout with a set of longitudinal seats at each end takes more time during evacuation than the layout with all transverse seats (*p* < 0.001). Therefore, it cannot be simply considered that the more transverse seats, the more it affects the flow of people. Figure 6 shows the evacuation diagram of these two seat layouts when other design factors are fixed. At the 16th second, the door area with longitudinal seats (Figure 6 (a)) is more crowded than the door area with all transverse seats (Figure 6 (b)). This is similar to the effect of increasing the width of the foyer. In evacuation, the wider the foyer is not the better. The too wide doorway area leads to the disorder of the flow of people, resulting in congestion.

Figure 6. The evacuation diagram of two seat layouts at the 16th second: (a) A layout with a set of longitudinal seats at each end; (b) A layout with transverse seats

**5.1.7. The influence of pole arrangement**

In previous studies, it has been a controversy whether the pole at door area has an effect on the flow of people. [34] and [51] believe that the pole at door area will hinder passengers from entering and exiting. Seriani and Fernandez [33] argue that the pole in the foyer can play a role in diversion, but they did not compare it with the situation where the pole is not installed at all, while [18] believes that it has no effect. We only considered the situation that the pole is on the central axis of the carriage and think that its impact on boarding and alighting can be ignored, but its impact on evacuation is very significant (*p* < 0.001). Of course, the design with the minimal effect on evacuation is to install no pole, but this reduces the service capacity of the carriage. Standing passengers mainly rely on handrails to maintain balance, and each pole can be used by multiple passengers [17]. It is necessary to set up poles in subway cars. From the perspective of taking into account the service demand, the layout of more poles can be selected from the schemes that do not have statistical differences. The design of one pole at the door area (Level 3) should be considered first, followed by two poles in front of the seat (Level 4), and finally the design of two poles in front of the seat with one pole at the door area (Level 6).

**5.2. Guidance on train design**

There is now a clear point of view to support our third purpose of completing this research: to guide train design. The range analysis gives the two optimal combinations of A2B2C2D3E2F1G1 and A1B2C1D3E3F1G5 for evacuation and boarding and alighting scenarios, which do not agree on the level of some factors. Through ANOVA and further discussion, we tried to integrate a carriage design with better performance in evacuation and boarding and alighting at the same time. The principle is to use the optimal level of design in the significant factors, and any level of design can be used in the insignificant factors. For the parameters with significant influence but inconsistent levels in both scenarios, the level of the scenario with the highest ranking of the factors shall be given priority (Figure 7).

Figure 7. The selection principle of factor level, $R\_{e(x\_{i})}$ is the range order of factor $x\_{i}$ in evacuation, $R\_{b(x\_{i})}$ is the range order of factor $x\_{i}$ in boarding and alighting; $x\_{ie}$ and $x\_{ib}$ represent the optimal level of factor $x\_{i}$ in evacuation and boarding and alighting scenarios.

In theory, we consider the parameter combination of wide vehicle (A2), asymmetric door (B2), connected carriage (C1), 1500 mm door (D3), 2050 mm foyer (E3), longitudinal seat (F1) and door area using one pole (G3). The carriage design scheme of new combination is not in the typical scheme of orthogonal experiments, which is a good signal. So we establish a digital model again to verify the scheme, and the results are shown in Figure 8. Compared with 36 experimental schemes, the new scheme takes the shortest time.

Figure 8. The performance of the new scheme in evacuation and boarding and alighting scenarios: (a) evacuation; (b) boarding and alighting

It should be emphasized that the purpose of this study is to provide guidance for train design, not to provide the optimal design scheme. The new scheme is just an example of how to guide the design through the research results. The specific parameters used to configure the carriage still depend on the actual operational requirements and engineering manufacturing constraints.

**6. Conclusion**

In this paper, the effect of design features inside the carriage on passenger evacuation and boarding and alighting time is studied. The passenger density of 6 pass/m2 was used to simulate the performance of different design parameters under extreme conditions. The walking speed of passengers in a fully loaded carriage was defined by real-life experiment and simulation experiment. The evacuation speed of 1.4 m/s and the boarding and alighting speed of 1.2 m/s could ensure that the simulation results are consistent with the experimental results of the real scenario. The mixed-level orthogonal experiment of seven carriage design factors was established, and the simulation results were analyzed by range analysis and ANOVA. Research showed:

1. The effect order of design factors on passenger evacuation and boarding and alighting is different. The order of influencing factors for evacuation is seat > door width > vehicle type > pole > foyer width > door symmetry > carriage connectivity; the order of influencing factors for boarding and alighting is: seat > door width > foyer width > pole > vehicle type > carriage connectivity > door symmetry.
2. Whether the carriages are connected or not has no significant impact on the evacuation, and other design factors have a very significant main effect on the evacuation time. The symmetry of the door, the connection of the carriage and the arrangement of the poles have no significant effect on the boarding and alighting time. The seat layout, door width and foyer width have strong significance. The effect of the vehicle type on the boarding and alighting is only significant at the level of *α* = 0.05. Seat and door width are the two main factors determining evacuation and boarding and alighting performance.
3. Wider doors have limited effect on time reduction. Similarly, the increase in the width of the foyer is not linearly related to the decrease in time. The foyer with medium width (1850 mm) is most conducive to evacuation but the worst effect of boarding and alighting. The layout of the longitudinal seats performs best in both scenarios. In addition to the layout of transverse seats, the layout of a set of longitudinal seats at each end of the carriage also got very poor performance. The effect on time of the carriage without pole is the same as that of the carriage with a pole only at the center of the door area.
4. The analysis results are used to guide the train design, and the principles for selecting parameters of carriage design that combine the ranking of factors’ effect and the degree of significance are proposed, and a new scheme is provided, which has achieved the best results in comparison with other schemes.

Finally, the study has some limitations. In fact, the reasons affecting the efficiency of passenger flow are very complex. Since our research purpose is to improve the carriages, other influencing factors are reduced as much as possible. The influence on evacuation and boarding and alighting time is discussed only in a single field of the geometric parameters of the carriage, which leads to the experimental results may not accurate. In addition, the parameters of the existing carriages were selected as factor levels in the experimental design, rather than all possible parameters, which means that the optimal parameters in the experiment can only represent the actual situation, rather than the theoretical optimal. This study has set the experimental scenario, and more situations will be considered in future research, such as double-sided boarding and alighting at the transfer station, boarding and alighting mode of opening doors in turn, boarding on one side and alighting on the other side, etc. And we will ​take further account of the interaction between variables.