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Experimental study on evacuation behaviour of passengers in a high-deck coach: A Chinese case study

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ABSTRACT

High-deck coaches form an essential component of mass transportation systems in China. Safe evacuation from high-deck coaches is facing dire challenges. However, evacuation behaviour from high-deck coaches has not been deeply understood yet. In this study, a novel conceptual framework is firstly proposed to capture the evacuation behaviour of coach passengers, and next based on which 22 full-scale experiments have been conducted to examine the effect of three selected factors: available exits, lighting conditions and age groups on the evacuation behaviour of Chinese passengers in a high-deck coach, in a systematic and quantitative way. Four performance indicators of evacuation behaviour, i.e., evacuation time, pre-evacuation time, flow rate and crowdedness, were collected and analysed. The results indicate that limited available exits and the dim lighting condition (less than 1 lux) significantly reduce the evacuation efficiency and increase the crowdedness within the aisle area regardless of the age groups. Compared to young students, the evacuation of middle-aged people is observed to have a significantly longer pre-evacuation time, lower evacuation efficiency, and higher level of crowdedness. In addition, young students' pre-evacuation times are found to conform to the Weibull distribution, whereas middle-aged people' pre-evacuation times could be modelled with the Loglogistic distribution. Empirical results of this study could be helpful for the improvement of the safety design of high-deck coaches, and provide valuable benchmarks for the development of coach evacuation behaviour and simulation models.

1. Introduction

With growing passenger demand for public transport, evacuation safety of passengers in case of emergencies has attracted extensive concerns from the scientific community. In many incidents, rapid and safe evacuations are effective and necessary measures to avoid or reduce deaths and injuries of passengers [1,2]. Previous studies on mass transport vehicles such as trains [3–8], school buses [9,10], suggested that there is a great challenge for passengers to evacuate rapidly and safely. Since coaches possess the common features as other vehicles (i.e., confined space, seat rows and narrow seat aisle), the evacuation from coaches could be complex and risky as well, deserved in-depth investigations.

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In China, to meet the increasing travel demand, modern coaches are almost high-deck coaches, with the upper deck for accommodating passengers and the lower deck for serving as a luggage compartment [11]. With the improvement of riding comfort, large coaches are gradually gaining popularity, with a 58% increase in the number from 2008 to 2018 [12]. However, according to the statistics of catastrophic road accidents (with more than 10 deaths) from 2015 to 2017 in China, high-deck coaches accounted for 34.4% of these accidents [13]. To cope with such high risks, specific regulations have been formulated in different countries [14]. Although the basic contents and principles of different regulations are identical, detailed provisions are diverse, resulting in the structural differences of high-deck coaches in different countries. Such differences in internal layouts and exit designs between countries would have important effects on the evacuation of passengers. Moreover, as indicated by Galea et al. [15] and Duives [16], cultural backgrounds are also likely to make a difference in passengers' evacuation behaviour. It is therefore essential to explore the evacuation behaviour of passengers in a high-deck coach under the specific coach safety regulation and cultural context.

To evaluate the evacuation performance of passengers using different exits in a coach, a series of full-scale or small-scale experiments (NB: experiments in which coaches are fully-loaded are referred to as *full-scale experiments*; otherwise, they are called as *small-scale experiments* in this paper) have been performed in different countries from 1970 to 2010, including America [14,17–19], UK [20], Germany [20], Japan [20] and Hungary [20]. Amongst these studies, small-scale experiments dominate. Recently, Abulhassan et al. [9] quantified the effect of available exits on the overall flow rate of a school bus by full-scale experiments. Nevertheless, the exit arrangement and configuration of school buses are totally different from that of coaches.

Visibility is another crucial factor affecting the evacuation movement and behaviour [21]. Limited visibility has been demonstrated to lead to lower evacuation efficiency and some characteristic evacuation behaviours such as reduction of velocity [21–23], tendency to walk along the boundary of walls or obstacles [22,24,25]. Accident statistics indicated that 20:00–24:00 pm is one of the time periods with the highest high-deck coach accident frequency [13]. One could imagine how the evacuation of passengers would be dangerous in such low lighting conditions coupled with accident factors such as injuries. Indeed, the Volpe Center, a federal agency under the U.S Department of Transportation, performed an exploratory study by small-scale experiments and suggested that the egress rates of the service door with stairs would significantly decline in low-light conditions (4–8 lux), especially in the dim lighting condition (0.2–0.6 lux). Fridolf et al. [4] also demonstrated that the flow rate of passengers through the train exit is affected by lighting conditions.

Besides, middle-aged and elderly passengers, with declining physical abilities, including mobility, vision, strength, etc., could have the poorly functional capacity to evacuate [26–29]. It has been suggested that special concerns should be paid to the ability of senior citizens to negotiate the height differential between the exit and the ground level in train safety [4,6]. Although stairways are designed to link the aisle to the ground in the coach, the stair pitch is far steeper than that in buildings [30]. Steeper stairs require higher physical ability for passengers, and in turn also result in higher fall risks [31]. Indeed, the only existing work indicated that elderly passengers had a significantly longer evacuation time in emergency door and emergency window evacuations [20]. However, it should be noted that these experiments did not test the service doors with stairways, which are widely equipped in modern coaches. Although the evacuation efficiency of middle-aged and elderly passengers through the service doors is also expected to be slower than that of young adults in coach scenarios, but to what extent is still unclear yet.

In summary, available exits, lighting conditions and age groups are proven to affect evacuation behaviour from mass transport vehicles, however, these three factors have not been systematically studied together in the high-deck coach complied with Chinese regulations. Therefore, firstly, this paper proposes a novel conceptual framework to identify the performance indicators and corresponding influential factors of evacuation behaviour from coaches and their theoretical cause–effect relationships. Secondly, based on four performance indicators selected from the conceptual model, for the first time, this work examines how the evacuation behaviour of Chinese passengers in a high-deck coach is affected by these three factors, in a systematic and quantitative way, via full-scale experiments. The third contribution is the presentation of the novel pre-evacuation time and instantaneous flow distribution data-sets that can be used to calibrate and validate the evacuation models and/or as empirical inputs of the commercial software by safety engineers.

Laboratory experiments and empirical observations are two potential approaches for evacuation behaviour data collection [32]. However, since the video recordings from the on-board CCTV (closed-circuit television) are inaccessible to the public, it seems to be impossible to obtain such data from empirical cases. The experiments then can easily be repeated in the same circumstances, and various specific situations/controlled variables can be produced and tested out [33]. Moreover, the monitoring will be easier, and the accuracy of data could be guaranteed [33]. Thus, for the purpose of this paper aforementioned, laboratory experiments will be a reasonable and practical choice.

The remainder of this paper starts with a conceptual modelling framework proposed to overview the overall performance indicators of evacuation behaviour, their corresponding influential factors and connections in the coach evacuation scenario in Section 2. Section 3 describes the detailed experimental setup, followed by the data processing and analysis plan in Section 4. The results of four performance indicators studied are presented and analysed in Section 5. Finally, the key findings and the corresponding implications for future research are discussed and concluded in Sections 6 and 7.

2. Conceptual modelling framework

The whole evacuation process in a high-deck coach consists of four parts (i.e., detection, warning, pre-evacuation and en-evacuation movement) [34]. Typically, the first two stages depend on the response of the on-board detection and warning devices or the driver to a large degree, which is out of the scope of this paper. Accordingly, this paper will only discuss passengers' behaviour in the pre-evacuation and en-evacuation movement stages. Correspondingly, as one of the performance indicators for the evacuation behaviour, the evacuation time consists of the time elapsed in the pre-evacuation stage (i.e., pre-evacuation time) and in the en-evacuation movement stage (i.e., movement time) [34].

In the pre-evacuation stage, pre-evacuation behaviour could be described by the actions and the elapsed times (as shown in the upper red-dashed box in Fig. 1), while the latter regarded as the final outcomes is typically used as the quantitative performance indicator. Three classes of determinants were summarized to have a potential influence on pre-evacuation actions, i.e., environmental conditions (physical and psychological) [29,35,36], commitments [35,37], and individual attributes [37], in which each determinant was decomposed as specific sub-elements in the lower layer (with dashed frame). Specifically, the coach layout refers to the design of emergency exits and corresponding guiding signs, which are expected to influence the time of passengers spent on looking for information used for initializing the evacuation [35]. A similar influence could also be caused by the environmental visibility. For other determinants or sub-elements, i.e., types of cue [35], passenger location [29,36], physiological environment [35], activity at pre-accident stage [35], activity at recognition stage [37], activity at response stage [37], and individual attributes [37], detailed definitions and/or explanations could be found in the corresponding references, which are not recapped here for the sake of simplicity. As highlighted in green/grey coloured boxes in Fig. 1, analyses in this part will focus on the potential effect of age and passenger position on the pre-evacuation time.

As for the en-evacuation movement behaviour, five performance indicators were identified from literature, i.e., movement time, flow rate, exit choice, velocity and crowdedness (as shown in the lower red-dashed box in Fig. 1). The original conceptual model of Duives [16] was extended and reconstructed to fit the coach evacuation scenario.

Theoretically, the movement time of a passenger is determined by the distance to the exit and the velocity, in which the distance to the exit is affected by the passenger location and the targeted exit choice. As suggested by empirical studies [38–41], the individual interactions were combined with the crowdedness within the aisle to adjust the velocity, under the limit of the maximum velocity. On one hand, the human physical capacity that controls the maximum velocity could be limited by individual attributes, including ***age*** [28,42–44], gender [45–47], cultural background [48,49] and health status [50–52]. On the other hand, environmental characteristics also make a difference in the free walking velocity of pedestrians, including the slope of the walkway [53,54] and the environmental visibility [21,22]. Practically, the floor slope in the high-deck coach can be varied, depending on the degree of the heeling and trim of the floor caused by incidents or road grades. This influential factor is dubbed the 'substratum conditions' here. Furthermore, Yamada and Akizuki [21] suggested that the environmental visibility is closely related to the visual object's conditions and the environmental conditions, which are affected by ***lighting conditions*** [22,54] and extinction coefficients [21,22].

Crowdedness within the aisle can be quantified by the number or the density of passengers within the aisle area [7]. Logistically, the two quantitative indicators both depend on the relative velocity of the inflow and outflow of passengers in the aisle. From this perspective, (a) the passenger load determining the overall passenger numbers waiting to enter the aisle [55], (b) the walking velocity of passengers limiting the flow rate, and (c) the structure characteristics affecting the movement of passengers, are three key influential factors of the crowdedness. Furthermore, the structure characteristics include the aisle width and ***the available exits*** that are featured by the exit numbers and configurations, determined by the coach safety regulation and the design passenger capacity. These may be varied in different countries or regions.

A large number of factors may have a potential influence on the exit choice, most of which are independent of other performance indicators. Thus, for sake of simplicity, only the factors that are unique to the coach scenario or already existing (in the conceptual model) were considered. Intuitively, the passenger location and the available exits will play a role on the exit choice of passengers, which is also affected by individual interactions, such as group behaviour [56].

As shown in Fig. 1, the conceptual model is proposed while considering and structuring all the aforementioned elements, which in turn provides the foundation for the current experiments and also the followed-up studies. For the purpose of this study, the quantitative performance indicators of the evacuation and pre-evacuation behaviour, i.e., ***evacuation time*** and ***pre-evacuation time***, are essential. As for the en-evacuation movement stage, the ***flow rate*** and the ***crowdedness*** were chosen as prior analyses indicate that it is tough to manually capture the movement start time and the velocity of passengers in the coach scenarios. Thus, four performance indicators denoted in blue colour and three influential factors coloured in green would be further investigated. Although the variable in grey colour (i.e., passenger location) is not the focus of this paper as its effect has been discussed by other researchers, the relevant results would be also recapped. From this conceptual model, the dependent and independent variables as well as their theoretical cause–effect relationships in this study, were clearly demonstrated. Therefore, the focus of this paper is to examine and quantify these relationships by full-scale experiments, described in the next section.

3. Experiment setup

As illustrated in the conceptual model, this study was dedicated to investigating the effect of available exits, lighting conditions and age on the evacuation behaviour of high-deck coach passengers. To this end, a total of 22 controlled experiments were designed and conducted.

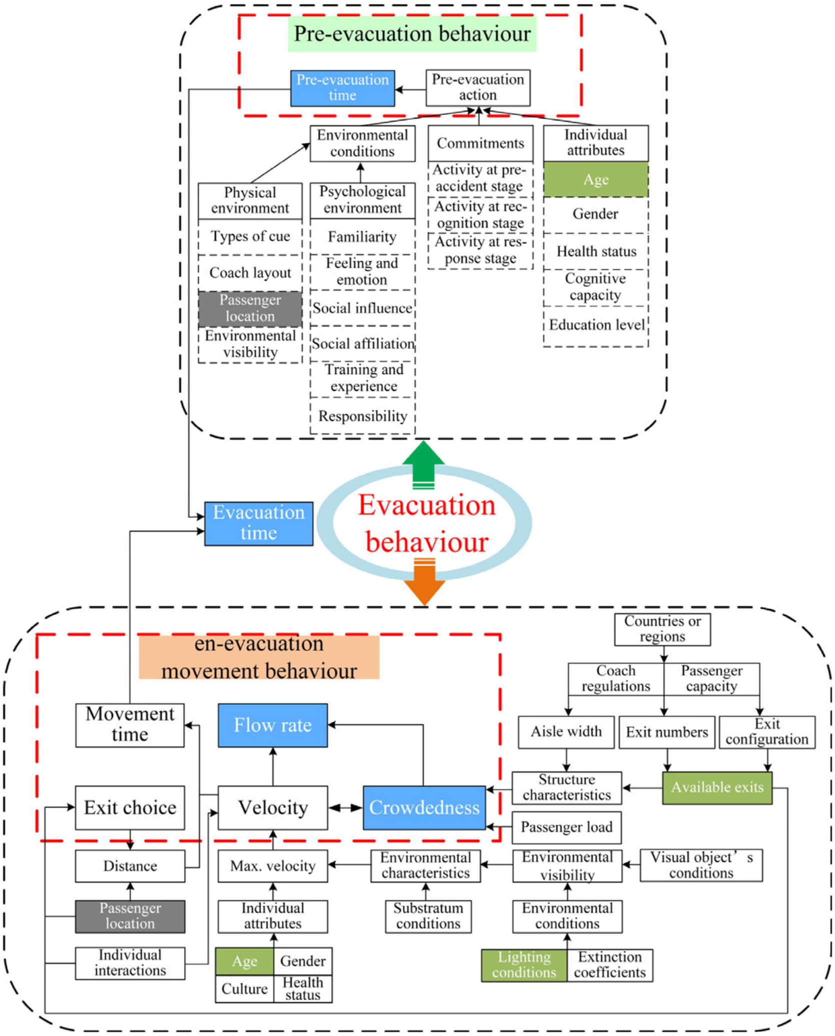


Fig. 1. Conceptual modelling on performance indicators and corresponding influential factors in high-deck coach evacuation scenarios. The connections are depicted by the arrowed lines.

3.1. Scenarios

Many combinations of the three independent variables could be identified, leading to more scenarios than those can be performed given time and cost constraints. Therefore, we selected the extreme values of the three variables that were believed to be critically helpful and realistically representative because important insights on the evacuation behaviour under the extremes of these variables could be established for high-deck coach evacuations in this way. Moreover, from the view of safety consideration and participants' willingness, it is not practical to recruit a group with an average age of more than 60 (the extreme of age groups), and thus a middle-aged group (towards elderly) was considered. Also, the experiments would only involve the evacuation through doors (not via windows or roof).

Accordingly, five cases of the available exits (i.e., only the front door opened, only the rear door opened, only the emergency door opened, the front and rear doors opened (as the extreme for high-deck coaches that have not installed the emergency door), and all three doors opened), two lighting levels (i.e., the normal and the dim lighting conditions) and two age groups (i.e., the young student and middle-aged people groups), were considered. The identified levels of three variables produce 20 potential combinations (5*2*2) in total, from which the experiments were finally determined. Specifically, evacuations in the dim lighting condition (the typical lighting level at night (i.e. 0.1–0.8lux) [30]) were prioritized as they represent a more dangerous situation than those in the normal lighting condition. Then, for safety reasons, the middle-aged people group was not involved in the experiments with emergency door evacuations. And, to reduce the effect of random factors as possible, each experiment would be repeated two times, with all passengers allocated to different seat positions in the repetitive experiments.

Table 1
The experimental scheme considering varying available exits, different lighting conditions, and two age groups.

Order	Available exits	Lighting conditions	Age groups
1	Three doors	Dim	Young students
2	Front and rear doors	Dim	Middle-aged people
3	Rear door	Dim	Young students
4	Rear door	Dim	Middle-aged people
5	Front and rear doors	Dim	Young students
6	Front and rear doors	Dim	Middle-aged people
7	Emergency door	Dim	Young students
8	Front door	Dim	Middle-aged people
9	Three doors	Dim	Young students
10	Front door	Dim	Middle-aged people
11	Front door	Dim	Young students
12	Rear door	Dim	Middle-aged people
13	Emergency door	Dim	Young students
14	Front and rear doors	Dim	Young students
15	Rear door	Dim	Young students
16	Front door	Dim	Young students
17	Front and rear doors	Normal	Middle-aged people
18	Front and rear doors	Normal	Middle-aged people
19	Front and rear doors	Normal	Middle-aged people
20	Front and rear doors	Normal	Young students
21	Front and rear doors	Normal	Young students
22	Front and rear doors	Normal	Young students

Thus, in the dim lighting condition, the young student group would be involved in 10 experiments (namely, experiments 1, 3, 5, 7, 9, 11, 13, 14, 15 and 16), whereas 6 experiments were designed for the middle-aged people group (namely, experiments 2, 4, 6, 8, 10 and 12). To compare the effect of lighting conditions, 3 repeated experiments with front-and-rear-door evacuations in the normal lighting condition (namely, experiments 17–22) were performed for the young student and middle-aged people groups, respectively. Therefore, the 22 experiments allow us to explore the solitary effect rather than any potential synergy effect of the three variables on evacuation behaviour. It should be noted that although two specific age groups rather than a mixed-age population were considered here, this study is still meaningful for the occasions that high-deck coaches serve for specific organizations, e.g., schools/universities, nursing homes, etc., in which the on-board passengers purely consist of young students/middle-aged (and elderly) people.

To minimize the effect of learning behaviour and fatigue, each group would participate in the experiments alternately. In addition, the first experiment of each age group was chosen to collect the pre-evacuation time data as a familiar environment (in repeated experiments) may potentially influence the pre-evacuation behaviour of passengers [34]. These two experiments were decided to be both conducted in the dim lighting condition as the resulted extreme values are preferable for engineering applications, and it could alleviate the pre-prepared actions of passengers in factitious laboratory scenarios by obstructing the acquisition of visual information and thus facilitate more realistic data collection. Finally, the experimental scheme was arranged as Table 1.

3.2. Layouts

Since most high-deck coach accidents happened on highways in China [13], the exit flow of passengers is more likely to be hindered by the highway railing or the lateral vehicle fleet rather than free of space during evacuations, especially in a tunnel. The hindered flow condition was then set as the basic scenario in our experiments to mimic the realistic high-deck coach evacuation process as possible.

The experimental layouts are shown in Figs. 2 and 3. A mockup of a tunnel, installed with blackout curtains in two entrances A and B, was used to artificially produce the dim lighting condition and the barriers hindering the exit flow of passengers. To minimize the likelihood of injury, the coach would remain static during the experiments [9,14]. The width of the walking corridor was 0.75 m, satisfying the minimum requirement of the lateral width for a one-way highway tunnel in China [57]. It indicates that our results can also provide valuable inputs for the evacuation risk assessment of one-way highway tunnels in the event of emergencies, such as fire. Moreover, two waiting areas were set in the tunnel to accommodate the participants evacuating from the coach temporarily.

A high-deck coach (Type: LCK6126H5QA1) produced in 2018, was used for our experiments. Currently, this model is one of the most representative high-deck coaches in China, officially designated as the service coaches of the World Military Games in Wuhan in 2019 (http://www.zhongtong.com/html/zxzx/gsxw/4172.html). The simplified design drawing of the interior arrangement is shown in Fig. 4. It can be seen that this high-deck coach has three doors, i.e., the front door, the rear door and the emergency door, labelled as F, R and E respectively. A total of 49 seats were arranged as 13 seat rows, in which some of the seat rows are not absolutely bilaterally symmetrical, such as row 2. However, it should be noted that such asymmetrical arrangements of partial seat rows have little effect on this study as our analyses were based on the comprehensive comparison of results from all seat rows in different experiments. 48 seats used for

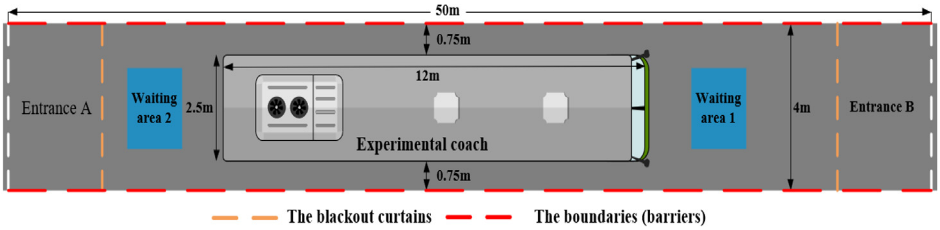


Fig. 2. Schematic illustration for the layout of the experimental field (a top-down view).

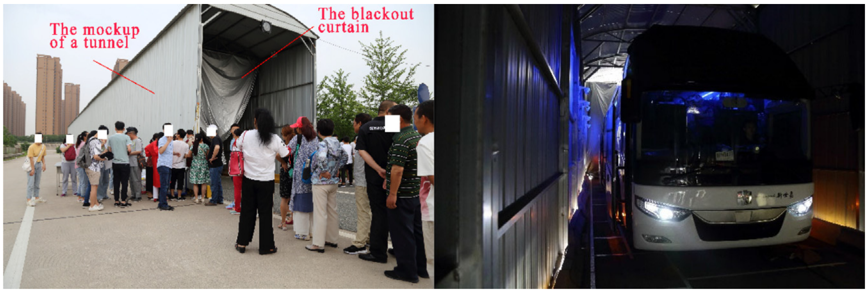


Fig. 3. Photos of the tunnel mockup and the experimental coach.

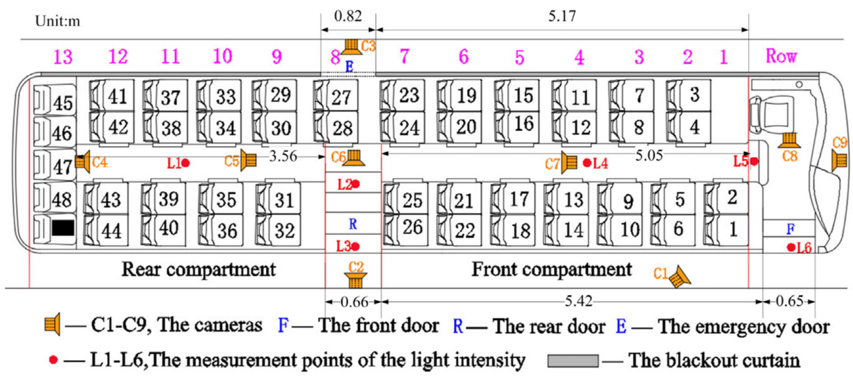


Fig. 4. The interior arrangement of the experimental coach.

Table 2
The light intensity measured at different locations inside the coach.

Location	Light intensity_1 (lux)	Light intensity_2 (lux)	Average (lux)
L1	0.23	0.35	0.29
L2	0.51	0.61	0.56
L3	0.70	1.00	0.85
L4	0.31	0.34	0.33
L5	0.43	0.51	0.47
L6	0.63	0.87	0.75

experiments were numbered and stuck with stickers of the corresponding number except for the last seat, where the video equipment was placed.

In addition, nine cameras equipped with infrared lights were set up in the high-deck coach and the tunnel mockup. To achieve the dim lighting condition in the experiments, the blackout curtain was also stuck to the left side of the experimental coach. The light intensity measurements were made at six locations before and at the end of the experiments, and the results are presented in Table 2. It can be seen that the average light levels were basically in the range of the typical level of illuminations provided by "night-lights" (i.e., 0.1–0.8 lux) [30]. Furthermore, the carriage was divided as the front compartment and the rear compartment for the analysis of the crowdedness within the aisle.

3.3. Participants

48 undergraduates and 48 middle-aged people who were physically fit were invited from the Department of Vehicle Engineering and a nearby residential community, forming the young student and middle-aged people groups respectively. No other detailed information was given except that they would participate in a series of outdoor experiments and be covered with the casualty insurance. Each group consisted of 28 men (58.3%) and 20 women (41.7%). The young students were aged between 20 and 23 years, with an average age of 21.4 years. The age of middle-aged people varied from 41 to 65 years, with an average age of 52.4 years.

A questionnaire investigation shows that 85.4% of the students ride high-deck coaches at least 1 to 4 times per year (and more), and this proportion is 93.7% for the middle-aged people group. Thus, these two groups can be reasonably considered as potential high-deck coach passengers, at least, with representativeness to some degree. Moreover, all participants had not experienced real or simulated coach evacuation drills, which ensures the credibility and validity of our data-sets.

3.4. Experimental procedures

After arriving at the experimental field, all subjects signed a prepared consensus agreement for their voluntary involvement in the experiments. Due to ethical reasons, participants were informed that they would participate in some high-deck coach evacuation experiments. However, they were not told how and when the experiments started and were instructed to make an evacuation decision based on their own judgements. Due to the hot weather in summer, the participants did not wear any coats or jackets, while some participants had their handbags with them during the experiments.

Each participant was assigned a different seat in different experiments to reduce the learning effect. After all participants sat in their seats, all lights inside the coach were turned off and the blackout curtains were pulled down for the experiments in the dim lighting condition, while these measures were removed for that in the normal lighting condition. Then, the driver kept the engine idling to simulate the normal driving condition, and the available doors remained open. At a random time (in 2-3 min), pre-recorded high-pitched voices extracted from a real-life accident (i.e., brakes screeching mixed with glasses shattered) were played out by on-board loudspeakers as the accident signal. At this point, the driver did not give any information other than stalling the engine. The participants exiting through the front and rear doors and the emergency door were led to waiting areas 1 and 2 respectively. After an experimental case finished, the group in the waiting areas was led to the outside, and another group entered the tunnel to prepare for the next experiment. Furthermore, a desk having a height of 80 cm was set outside the emergency door to reduce potential risks. Thus, young students would first jump from the floor to the desk (an 82-cm height) and then step down on the ground by a chair in emergency door evacuations.

4. Data processing and analysis plan

The experimental data were manually extracted from the video footage that filmed the evacuation at a frequency of 25 frame/s. Specifically, exterior cameras C1–C3 were used to determine the evacuation times and the flow rates, while interior cameras C4–C9 were responsible for recording the evacuation behaviour inside the coach. In this way, evacuation time, pre-evacuation time, flow rate and crowdedness, were collected.

4.1. Evacuation time

A passenger was identified to have evacuated the coach when his/her both feet had landed at the ground (or desk) [4], as shown in Fig. 5(a), (b) and (c). By cameras C1–C3, the time frame related to each passenger's arrival was noted and transcribed into the spreadsheet to calculate the evacuation time. As indicated in the conceptual model, all three independent variables and passenger locations were expected to have an influence on the evacuation time, which would be discussed in the next section detailedly.

4.2. Pre-evacuation time

Different from previous studies [34,58–60], the movement delay could exist between the end of the pre-evacuation phase and the moment of the purposeful movement towards an exit in our experiments, as the initial evacuation movement of passengers could be constrained by others standing in the aisle or sitting in the neighbouring seat. To exclude the effect of the movement delay, the pre-evacuation time in this paper is determined as the time from the start of the alarm to the time at which the passenger is considered ready to initiate the purposeful movement towards an exit [61].

As aforementioned, experiments 1 and 2 (in the dim lighting condition) were selected to collect the pre-evacuation times after careful consideration in three aspects (i.e., time and cost, engineering applications and data collection). By analysing the behavioural sequence of passengers in the pre-evacuation phase prior to the formal collections, releasing the seat belt was identified as the sign of responding to the evacuation. After this action, the pre-evacuation phase was

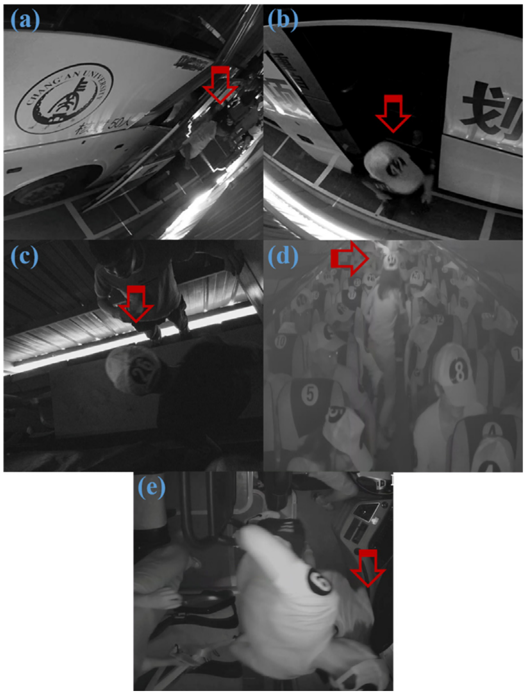


Fig. 5. Snapshots of data extraction. Scenes (a), (b), (c), (d) and (e) were taken by C1, C2, C3, C9 and C8, respectively. In snapshot (a), passenger 23 exited the coach from the front door. In snapshot (b), passenger 42 evacuated the coach from the rear door. In snapshot (c), passenger 26 landed at the desk. In snapshots (d) and (e), passengers 17 and 9 entered and exited the front aisle, respectively.

considered to be completed when a passenger exhibited the purposeful behaviour preparing to move towards an exit (e.g., turning his/her body to face the travel direction) whether he/she had stood up or sat at the seat location [61]. For each passenger, the time at which such the purposeful behaviour occurred was determined by analysing his/her whole behavioural sequence during evacuations. The collected pre-evacuation times would be dedicated to examining the effect of age groups and the distance to the closest exit in the pre-evacuation phase.

4.3. Flow rate

Different methods have been proposed to calculate the flow rate of occupants passing through a specific section [6,38,62,63], in which deterministic calculations that produce a constant flow value are prevailing. However, it is observed considerable variations for the instantaneous flow rates in our experiments as indicated in Section 5.3. A probabilistic approach that comprehensively considers the variations is likely to be more accurate to evaluate the overall evacuation performance in certain scenarios. Recently, a probabilistic distribution has been gradually recognized as a better measurement of evacuation performance in the fire safety community [60,64]. Moreover, it is vital to incorporate the difference of individual physical abilities in the representative flow rate data-sets due to the public attribute of high-deck coaches. Thereby, a stochastic variable was used to produce the flow distributions of passengers in different scenarios [6]. In this study, the flow rate was defined as the number of evacuated passengers per unit time. Correspondingly, the definition of the instantaneous flow rate F_s (per/s) is as in Eq. (1). This variable can reflect the time headway between two consecutive egressing passengers, and thus can determine the (theoretical) door capacity [65].

$$F_s = \frac{f}{\Delta G(i, i-1)} \quad (1)$$

where f is the frame rate (25 frames/s in this study), and $\Delta G(i, i-1)$ is the frame difference between the two passengers consecutively egressing from the coach, which can be straightforwardly calculated by the collected arrival time frame of each passenger.

As the three doors are located far apart and/or have an independent guiding passage respectively, it is reasonable to assume that evacuations from different doors are basically independent. Therefore, the flow rates from 22 experiments were combined to generate 14 flow samples, based on which statistical analyses (including paired comparisons and a multiple regression analysis) on the effect of available exits, lighting conditions and age groups would be conducted.

Moreover, data pre-processing is required to eliminate the outliers from original data samples. Given that the flow distributions are often skewed [6], the outliers were detected by the adjusted boxplot considering the med couple in this study [66–68].

4.4. Crowdedness

Specific indicators have been used to quantify the crowdedness within the aisle, including the instantaneous population and the linear density within the aisle [7]. However, both these indicators did not consider the duration of crowdedness, which is also a significant factor determining the level of crowdedness. Moreover, as the density at the beginning and the end of the evacuation is unstable, only the stable phase of the linear density curve is considered here. The stable phase is defined as the period when the linear density of the aisle fluctuates around a specific value (usually the maximum value), which is determined by observing the density curve. Then, the cumulative linear density (CLD) (in s per/m) is formulated to quantify the crowdedness within the aisle, calculated as follows

$$L_C^i = \int D_t^i dt \tag{2}$$

where L_C^i is the CLD of aisle i (in s per/m) in the stable phase; D_t^i is the instantaneous linear density of aisle i (in per/m) as a function of time t (in s), and $D_t^i = \frac{N_t^i}{\Delta L^i}$; N_t^i is the number of passengers in aisle i at time t, and ΔL^i is the length of aisle i (in m).

Along with the CLD, the average maximum linear density (AMLD) (i.e., the average density value in the stable phase) and the duration of the stable phase (DSP) were calculated and presented. An example of the calculation of the CLD, the AMLD and the DSP is illustrated in Appendix. The aisle of the front and rear compartments is 5.05 m and 3.56 m long, respectively. By the interior cameras, the time frame/moment when all parts of a participant's body had entered or exited the aisle could be extracted, as shown in Fig. 5(d) and (e). Thus, N_t^i can be calculated indirectly. And, the effect of available exits, lighting conditions and age groups on the crowdedness within the aisle would be discussed.

4.5. Summary

In this way, experimental data were collected to elaborate the effect of available exits, lighting conditions and age groups on the evacuation behaviour (evacuation time) and the en-evacuation movement behaviour (flow rate and crowdedness), and the effect of age on the pre-evacuation behaviour (pre-evacuation time).

5. Results

In this section, the data collected in the previous section will be presented and analysed sequentially to illustrate the effect of three independent variables.

5.1. Evacuation time

Because the varying response time (of the first respondent) and the inactive behaviour (at the end of the queues) of passengers that were observed in the experiments could lead to considerably unpredictable variances in overall evacuation times, only qualitative statistics analyses (paired comparisons rather than regression analysis) were conducted on evacuation times to determine the effect of available exits, lighting conditions and age groups. Also, the time when the first passenger exited the high-deck coach was regarded as the start of experiments to exclude the interference of the variance of the first response time in experiments. In addition, only 7 young students exited the coach by the emergency door in experiment 1, while this number is 13 in experiment 9 (the second times for the same experimental setting). This may be attributed to passengers' unfamiliarity with the emergency door as it is not used in normal conditions. This phenomenon also means that the learning behaviour is observed. Since such a result will significantly underestimate the effect of the three available doors, experiment 1 was excluded in our analyses but only presented here. Thus, the effect of learning behaviour on the analysis on evacuation time may be rather limited, as also demonstrated in Section 5.3.

Fig. 6 shows the graphical results of paired comparisons, in which the average evacuation time is represented as a function of the seat row number. As for the effect of available exits, comparisons could only be performed in two paired cases (i.e., (a) and (b)), as the spatial distribution of evacuation times is different for other experiments. These two paired comparisons show that passengers in the rear door and three-door evacuations generally have shorter evacuation times than that in the corresponding counterpart. Since passengers from seat rows 7 to 14 in experiment 1 made good use of the emergency door, a higher evacuation efficiency is also observed for them than that in experiment 9. More analyses regarding the effect of available exits will be conducted in Section 5.3. It is also evident that longer evacuation times are obtained in the dim lighting condition regardless of the age groups, and that middle-aged people generally evacuate at a slower evacuation efficiency than young students. Additionally, the mean evacuation times show an increasing trend as the distance of seat rows to the nearest available exits increases.

The qualitative observations described above are demonstrated by the paired-samples t-test of average evacuation times. The null hypothesis can be expressed as follows: available exits, lighting conditions and age groups have no significant effect on passengers' evacuation time. As shown in Table 3, the null hypothesis is not supported for all tests at the significance level of 5% or lower.

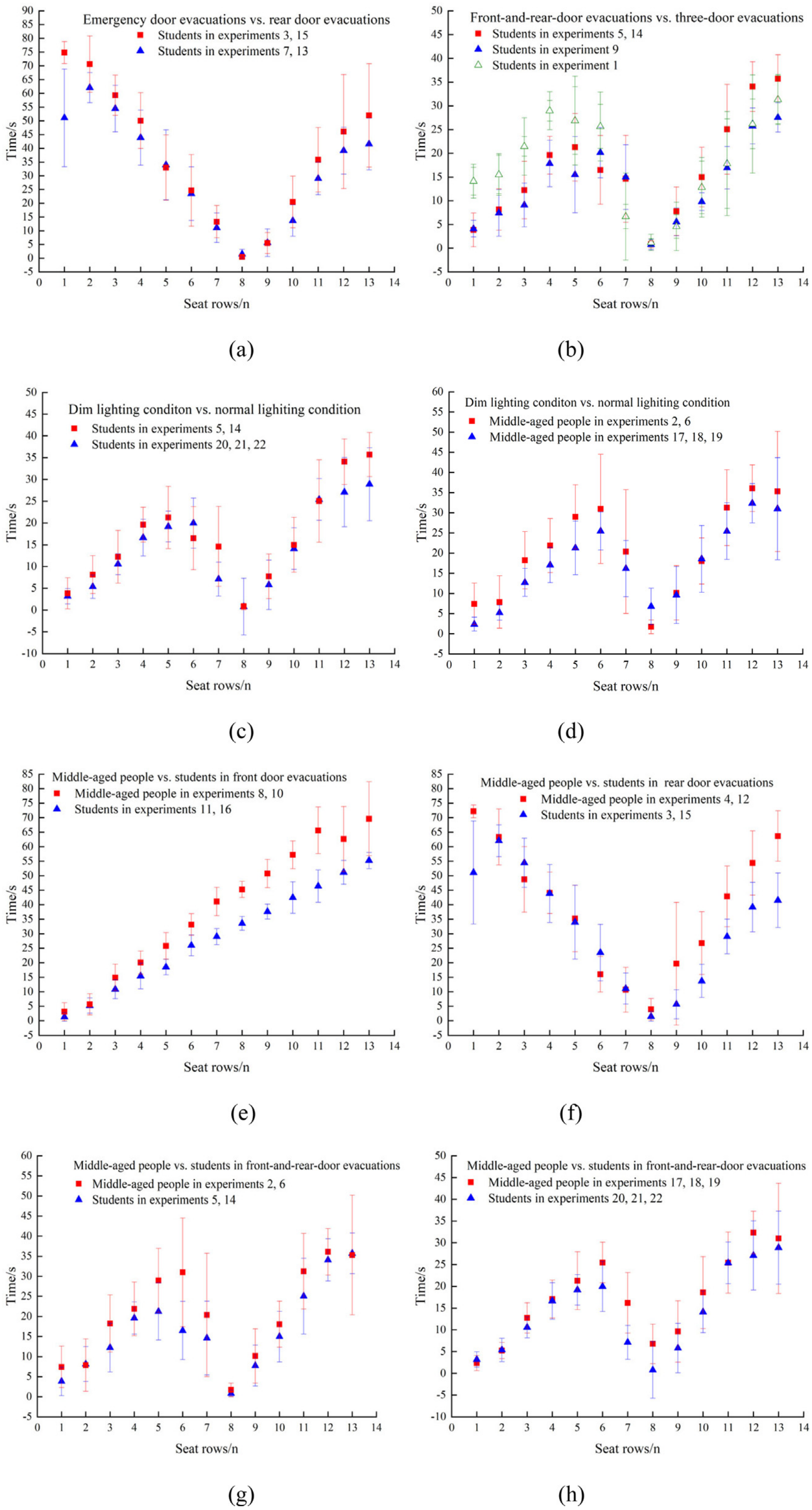


Fig. 6. Paired comparisons of evacuation times.

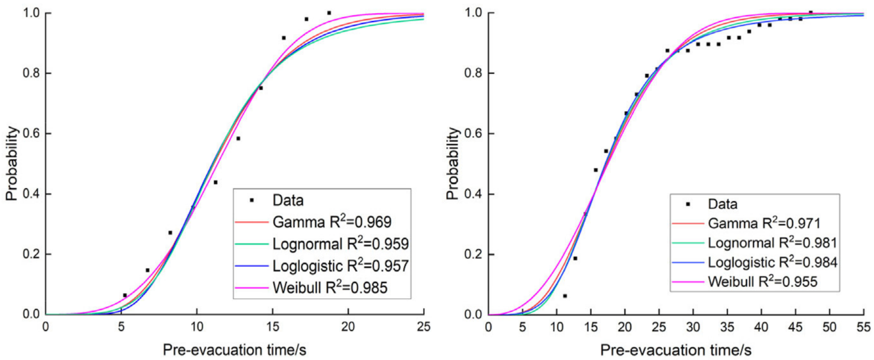
Table 3
Results of statistical tests for paired comparisons.

Pair	Mean (s)	S.D. (s)	P-value	H0
a	5.81	6.57	0.008	Reject[b]
b	3.01	3.82	0.015	Reject[a]
c	2.35	3.17	0.020	Reject[a]
d	3.40	3.36	0.003	Reject[b]
e	9.39	5.62	0.000	Reject[c]
f	6.99	9.94	0.026	Reject[a]
g	4.13	4.01	0.003	Reject[b]
h	3.08	2.91	0.002	Reject[b]

[a]indicates $P < 0.05$.
[b]indicates $P < 0.01$.
[c]indicates $P < 0.001$.

Table 4
The descriptive statistics of pre-evacuation times.

Data type	Number	Minimum	Maximum	Mean	Standard deviation	Skewness
Young students	48	5.32 s	18.64 s	11.92 s	3.75 s	−0.24
Middle-aged people	48	11.08 s	46.80 s	20.09 s	8.50 s	1.625



(a) Young students (b) Middle-aged people

Fig. 7. The pre-evacuation time probability distributions.

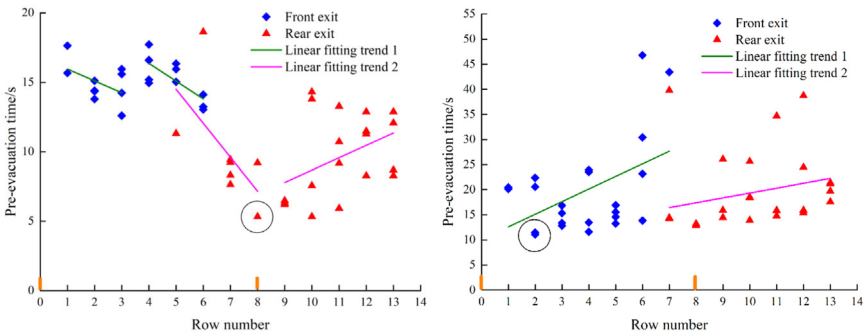
5.2. Pre-evacuation time

As presented in Table 4, the average pre-evacuation time of students is 11.92 s, ranging between 5.32 s and 18.64 s, while that of middle-aged people is 20.09 s, ranging from 11.08 s to 46.80 s. Their difference in the pre-evacuation is statistically significant according to the Welch's t-test (t (64.60) = −6.09, $p < 0.001$) [69]. The results indicate that middle-aged people generally have much longer pre-evacuation times when compared to young students in our experiments. Using the method proposed by Lovreglio et al. [70], the pre-evacuation times of young students and middle-aged people were estimated, the results of which are presented in Fig. 7 and Table 5. It is found that the Weibull distribution provides the best fitting performance for students' pre-evacuation times whereas the Loglogistic distribution for middle-aged people' pre-evacuation times. However, due to limited data, more experiments are required to identify the underlying reasons accounting for the difference of pre-evacuation between young students and middle-aged people. Moreover, when employing the distributions, it should be noted that the data used for parameter estimations were obtained from an experimental scenario using participants within a specific age range (i.e., young students aged 20–23 and middle-aged people aged 41–65).

The pre-evacuation time spatial distributions based on seat row numbers are depicted in Fig. 8. In these plots, the aimed exits for the initial movement were classified as the front exit and the rear exit, which includes the rear and emergency doors as they have a similar longitudinal location. Also, the linear fitting trend lines have been drawn for better visualization. It is clearly visible that the pre-evacuation times of experiments 1 and 2 show totally different spatial distributions, which are closely related to the location of the person first moving to the exit during evacuations. This might be because of the effect of social influence [37,60]. It is observed that passengers who responded early hesitated and tended to look at the neighbours' reactions to confirm their own judgements when the alarm was triggered. Thus,

Table 5
Estimated parameters of pre-evacuation distributions.

Evacuees	Distribution	Parameters		R2
		a (μ)	b (σ)	
Young students	Gamma	8.12	1.43	0.969
	Lognormal	2.40	0.35	0.959
	Loglogistic	2.40	0.21	0.957
	Weibull	12.72	3.23	0.985
Middle-aged people	Gamma	5.60	3.29	0.971
	Lognormal	2.84	0.42	0.981
	Loglogistic	2.84	0.25	0.984
	Weibull	20.30	2.46	0.955



(a) Young students (experiment 1) (b) Middle-aged people (experiment 2)

Fig. 8. The pre-evacuation time spatial distributions based on seat row numbers. The first person moving to the exit is marked by a black circle. The front and rear exits are located in rows 0 and 8, respectively, denoted by the short orange lines.

the responding action propagated from the position of the first respondent along the long and confined carriage bi-directionally. Since some passengers in row 3 responded as fast as that in row 6 in experiment 1, two parallel propagations of the responding behaviour (i.e., from row 3 to row 1 and from row 6 to row 4, respectively) occurred for passengers initially moving towards the front exit, as indicated by the two green fitting lines in Fig. 8(a). Moreover, varying response times of the first respondent are observed in different experiments, and relatively shorter response times are observed in the later experiments as compared to the first experiments regardless of the age groups. It means that the learning behaviour is also observed in this regard. And this observation justifies the choice of using the first experiments to collect pre-evacuation time.

Additionally, the trend lines indicate that the pre-evacuation times have an overall trend increasing with the distance of seat rows to exits [29,36]. Except for the intentional waiting behaviour of passengers with unfavourable locations [36], our observations imply that this may also be related to social influence.

5.3. Flow rate

The statistical parameters of instantaneous flow distributions are shown in Table 6, where $F_{P\_B\_C}$ denotes the sample of flows P-group (ST-young student group or MA-middle-aged people group), B-door (F-front door, R-rear door, E-emergency door, FR-front-and-rear door or FRE-front-rear-and-emergency door) and C-condition (D-dim lighting condition, N-normal lighting condition). The mean value of each distribution could be regarded as the average flow rate. The Coefficient of Variation for all flow samples is well over 15%, which demonstrates the necessity of considering the variation of instantaneous flow rates. The novel flow distribution data-sets presented could allow one to calibrate and validate the probabilistic outcomes of simulation models. It is worth noting that evacuation models currently are requiring distributions to represent the exit performance in the assessment [36,60].

To determine the effect of available exits, lighting conditions and age groups on the average flow rate, the non-parametric hypothesis tests of paired samples were conducted using the Mann–Whitney–Wilcoxon (MWW) [71,72], the Two-sample Kolmogorov–Smirnov (K–S) test [73] and the Welch's t-test (Welch) [69]. The null hypothesis is that there is no significant difference between the paired flow samples. As shown in Tables 7–9, The H0 is rejected by MWW, K–S and Welch statistical tests for all paired comparisons except for the pairs that are in bold at the significance level of 5%. The results indicate that while the statistically significant difference is observed between the flow rate of the front and rear doors for young students, such a difference is not apparent for middle-aged people. As explained in Appendix, the design of the front door stairways might contribute to the higher flow rate of young students.

Table 6
Statistical parameters of instantaneous flow distributions.

Flow type	Number	Mean (per/s)	S.D. (per/s)	Coefficient of Variation	95% confidence interval (per/s)	Skewness	Kurtosis
$F_{ST\_F\_D}$	151	0.80	0.19	23.8%	[0.77,0.83]	−0.12	−0.49
$F_{ST\_R\_D}$	191	0.76	0.20	26.3%	[0.73,0.79]	0.38	0.41
$F_{ST\_E\_D}$	107	0.64	0.16	25.0%	[0.61,0.67]	0.36	−0.44
$F_{MA\_F\_D}$	130	0.66	0.20	30.3%	[0.63,0.70]	0.83	0.10
$F_{MA\_R\_D}$	143	0.65	0.18	27.7%	[0.62,0.69]	0.52	−0.29
$F_{ST\_FR\_D}$	80	1.26	0.62	51.2%	[1.12,1.39]	0.97	0.037
$F_{ST\_FRE\_D}$	82	1.68	1.09	64.9%	[1.44,1.92]	1.15	0.43
$F_{MA\_FR\_D}$	79	1.01	0.47	46.5%	[0.90,1.11]	1.46	3.70
$F_{ST\_F\_N}$	56	0.91	0.26	28.6%	[0.84, 0.98]	−0.07	−0.88
$F_{ST\_R\_N}$	77	0.81	0.15	18.5%	[0.78, 0.85]	0.06	−0.64
$F_{ST\_FR\_N}$	104	1.53	0.83	54.2%	[1.37, 1.69]	1.48	1.17
$F_{MA\_F\_N}$	60	0.71	0.18	25.3%	[0.66, 0.75]	0.38	−0.24
$F_{MA\_R\_N}$	73	0.70	0.15	23.9%	[0.67, 0.73]	0.19	−0.31
$F_{MA\_FR\_N}$	102	1.29	0.72	55.8%	[1.15, 1.43]	1.39	0.76

Table 7
Results of statistical tests for the effect of available exits.

Paired samples		MWW		K–S		Welch	
		Statistics comparison	H0	Statistics comparison	H0	Statistics comparison	H0
$F_{ST\_F\_D}$	$F_{ST\_R\_D}$	−2.40 < −1.96	Rejected	0.151 > 0.148	Rejected	2.12 > 1.965	Rejected
$F_{ST\_R\_D}$	$F_{ST\_E\_D}$	−5.19 < −1.96	Rejected	0.342 > 0.164	Rejected	5.77 > 1.965	Rejected
$F_{ST\_E\_D}$	$F_{ST\_FR\_D}$	8.71 > 1.96	Rejected	0.637 > 0.199	Rejected	−8.61 < −1.987	Rejected
$F_{ST\_FR\_D}$	$F_{ST\_FRE\_D}$	2.03 > 1.96	Rejected	0.214 > 0.213	Rejected	−3.08 < −1.972	Rejected
$\mathbf{F_{MA\_F\_D}}$	$\mathbf{F_{MA\_R\_D}}$	**-0.16 > -1.96**	Accepted	**0.065 < 0.165**	Accepted	**0.42 < 1.965**	Accepted
$F_{MA\_R\_D}$	$F_{MA\_FR\_D}$	7.02 > 1.96	Rejected	0.495 > 0.191	Rejected	−6.47 < −1.984	Rejected
$F_{MA\_F\_D}$	$F_{MA\_FR\_D}$	7.35 > 1.96	Rejected	0.542 > 1.93	Rejected	−6.87 < −1.987	Rejected
$F_{ST\_F\_N}$	$F_{ST\_R\_N}$	−2.34 < −1.96	Rejected	0.283 > 0.238	Rejected	2.44 > 1.987	Rejected
$F_{ST\_R\_N}$	$F_{ST\_FR\_N}$	8.79 > 1.96	Rejected	0.619 > 0.203	Rejected	−8.58 < −1.972	Rejected
$\mathbf{F_{MA\_F\_N}}$	$\mathbf{F_{MA\_R\_N}}$	**0.113 < 1.96**	Accepted	**0.100 < 0.159**	Accepted	**0.026 < 1.984**	Accepted
$F_{MA\_R\_N}$	$F_{MA\_FR\_N}$	7.87 > 1.96	Rejected	0.553 > 0.208	Rejected	−7.96 < −1.984	Rejected

Table 8
Results of statistical tests for the effect of lighting conditions.

Paired samples		MWW		K–S		Welch	
		Statistics comparison	H0	Statistics comparison	H0	Statistics comparison	H0
$F_{ST\_F\_D}$	$F_{ST\_F\_N}$	2.80 > 1.96	Rejected	0.268 > 0.213	Rejected	−2.79 < −1.994	Rejected
$F_{ST\_R\_D}$	$F_{ST\_R\_N}$	2.43 > 1.96	Rejected	0.188 > 0.182	Rejected	−2.50 < −1.984	Rejected
$F_{ST\_FR\_D}$	$F_{ST\_FR\_N}$	2.47 > 1.96	Rejected	0.204 > 0.202	Rejected	−2.57 < −1.994	Rejected
$F_{MA\_F\_D}$	$F_{MA\_F\_N}$	2.18 > 1.96	Rejected	0.215 > 0.212	Rejected	−2.48 < −1.984	Rejected
$F_{MA\_R\_D}$	$F_{MA\_R\_N}$	2.27 > 1.96	Rejected	0.206 > 0.196	Rejected	−2.14 < −1.984	Rejected
$F_{MA\_FR\_D}$	$F_{MA\_FR\_N}$	2.06 > 1.96	Rejected	0.208 > 0.204	Rejected	−3.19 < −1.972	Rejected

Table 9
Results of statistical tests for the effect of age groups.

Paired samples		MWW		K–S		Welch	
		Statistics comparison	H0	Statistics comparison	H0	Statistics comparison	H0
$F_{ST\_F\_D}$	$F_{MA\_F\_D}$	−5.94 < −1.96	Rejected	0.358 > 0.162	Rejected	5.99 > 1.972	Rejected
$F_{ST\_R\_D}$	$F_{MA\_R\_D}$	−4.99 < −1.96	Rejected	0.244 > 0.150	Rejected	5.31 > 1.972	Rejected
$F_{ST\_FR\_D}$	$F_{MA\_FR\_D}$	−2.31 < −1.96	Rejected	0.223 > 0.152	Rejected	2.84 > 1.984	Rejected
$F_{ST\_F\_N}$	$F_{MA\_F\_N}$	−4.33 < −1.96	Rejected	0.440 > 0.253	Rejected	4.91 > 1.987	Rejected
$F_{ST\_R\_N}$	$F_{MA\_R\_N}$	−4.17 < −1.96	Rejected	0.334 > 0.222	Rejected	4.55 > 1.984	Rejected
$F_{ST\_FR\_N}$	$F_{MA\_FR\_N}$	−3.43 < −1.96	Rejected	0.260 > 0.190	Rejected	2.21 > 1.972	Rejected

Based on the statistical results, it could be concluded that available exits and lighting conditions significantly affect the evacuation flow rate, and a statistically significant difference is shown in the evacuation efficiency between young students and middle-aged people.

Table 10
Reduction coefficients of flow rate and corresponding confidence intervals.

Evacuees	Paired samples		R	$R\|_{\min}$	$R\|_{\max}$
Young students	$F_{ST\_FR\_D}$	$F_{ST\_FRE\_D}$	0.25	0.03	0.42
	$F_{ST\_F\_D}$	$F_{ST\_FRE\_D}$	0.52	0.42	0.60
	$F_{ST\_R\_D}$	$F_{ST\_FRE\_D}$	0.55	0.45	0.62
	$F_{ST\_E\_D}$	$F_{ST\_FRE\_D}$	0.62	0.53	0.68
	$F_{ST\_F\_D}$	$F_{ST\_F\_N}$	0.12	0	0.21
	$F_{ST\_R\_D}$	$F_{ST\_R\_N}$	0.06	0.01	0.14
	$F_{ST\_FR\_D}$	$F_{ST\_FR\_N}$	0.18	0	0.34
Middle-aged people	$F_{MA\_F\_D}$	$F_{MA\_FR\_D}$	0.35	0.30	0.44
	$F_{MA\_R\_D}$	$F_{MA\_FR\_D}$	0.36	0.31	0.44
	$F_{MA\_F\_D}$	$F_{MA\_F\_N}$	0.07	0	0.16
	$F_{MA\_R\_D}$	$F_{MA\_R\_N}$	0.07	0	0.15
	$F_{MA\_FR\_D}$	$F_{MA\_FR\_N}$	0.22	0.03	0.37
Young students and middle-aged people	$F_{MA\_F\_D}$	$F_{ST\_F\_D}$	0.18	0.09	0.24
	$F_{MA\_R\_D}$	$F_{ST\_R\_D}$	0.14	0.05	0.22
	$F_{MA\_FR\_D}$	$F_{ST\_FR\_D}$	0.23	0.02	0.39
	$F_{MA\_F\_N}$	$F_{ST\_F\_N}$	0.22	0.11	0.33
	$F_{MA\_R\_N}$	$F_{ST\_R\_N}$	0.14	0.06	0.21
	$F_{MA\_FR\_N}$	$F_{ST\_FR\_N}$	0.16	0	0.32

To quantify the difference, a reduction coefficient of flow rate R was introduced in this study, shown as follows:

$$R = \frac{M_i - M_j}{M_i} \tag{3}$$

where M_i and M_j are the mean values of the flow distributions i and j.

Analogously, a confidence interval of R was also presented to emphasize the uncertainties. Let α is the significance level of the confidence interval of M. Thus, the confidence probability of the confidence interval of R can be calculated by $P_C = P(R|_{\min} < R < R|_{\max}) = (1 - \alpha/2)^2$ [6].

In this paper, $\alpha = 0.05$, thus, $P_C = 0.9506$. The reduction coefficients calculated are provided in Table 10. The effect of available exits and lighting conditions on the en-evacuation movement is clearly visible. Compared with three doors simultaneously opened, the total flow rate decreases by 62% on average in the emergency door evacuation. A significant decrease of the average flow rate is also spotted for middle-aged people compared with young students, with a maximum average drop of 23% obtained in the front-and-rear-door evacuation. Moreover, a considerable reduction of the flow rate caused by the dim lighting condition is found for both young students and middle-aged people, with the maximum average decrease of 18% and 22% achieved in the front-and-rear-door evacuation respectively.

A multiple regression analysis was performed, the results of which are shown in Table 11. In this regression analysis, the scenario with three doors opened, the normal lighting condition and young students was set as the reference case, where an average maximum flow rate (1.815 per/s) is achieved. The negative signs of coefficients demonstrate that limited available exits (less than three doors), the dim lighting condition and middle-aged people significantly prolong the en-evacuation movement. As compared to the scenario of having three doors available, on average, the scenario with only the emergency door opened results in the maximum decrease of the flow rate (−1.04 per/s), followed by the scenarios with only the rear door opened (−0.93 per/s), only the front door opened (−0.89 per/s), and both front and rear doors opened (−0.389 per/s). The results indicate that the front door evacuation has a slightly higher flow rate (0.04 per/s) than the rear door evacuation on average, which may be explained by the less steep front door stairways (as shown in Appendix). Also, the dim lighting condition reduces the flow rate by an average of 0.14 per/s, and an average decrease of 0.177 per/s is observed for middle-aged people as compared to young students. Furthermore, the three independent variables well explain 95.2% variability of the flow rate in our experiments, and thus it demonstrates the capability of predicting the evacuation flows with these variables. A proper learning effect could contribute to less fluctuation of the evacuation behaviour [74], and thus the flow rate can be predicted much better as shown in this work, leading to a high R square value. On the other hand, it also implies that the promoting effect of the learning behaviour during the evacuation process on flow rates may be rather limited.

The regression equation: flow rate (per/s) = 1.815 + 0.0 × (three doors available) −0.890 × (only the front door available) −0.930 × (only the rear door available) −1.040 × (only the emergency door available) −0.389 × (the front and rear doors available) + 0.0 × (the normal lighting condition) −0.140 × (the dim lighting condition) + 0.0 × (the young student group) −0.177 × (the middle-aged people group).

5.4. Crowdedness

The higher the CLD is, the more crowded it is for the aisle area in the evacuation. Fig. 9 shows the CLD with varying available exits, lighting conditions, and age groups. It is clearly observable that the limited available exits and the dim

Table 11
Multiple regression coefficients of flow rates (Ad. R^2 = 0.952).

Model	Coef.	SE coef.	T-value	*P*-value	VIF
Constant	1.815[c]	0.087	20.813	0.000	
Available exits					
Front door	−0.890[c]	0.090	−9.901	0.000	4.048
Rear door	−0.930[c]	0.090	−10.346	0.000	4.048
Emergency door	−1.040[c]	0.107	−9.737	0.000	1.857
Front and rear doors	−0.389[b]	0.009	−4.311	0.004	4.048
Lighting conditions					
Dim lighting condition	−0.140[a]	0.044	−3.096	0.017	1.143
Age groups					
Middle-aged people	−0.177[b]	0.044	−4.014	0.005	1.143

[a]indicates $P < 0.05$.
[b]indicates $P < 0.01$.
[c]indicates $P < 0.001$.

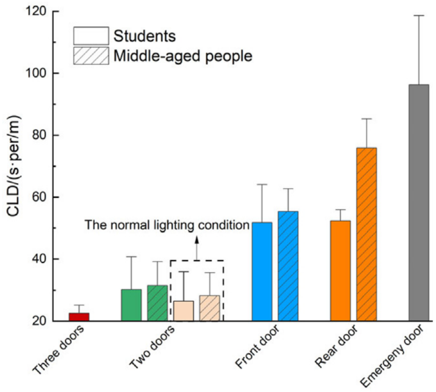
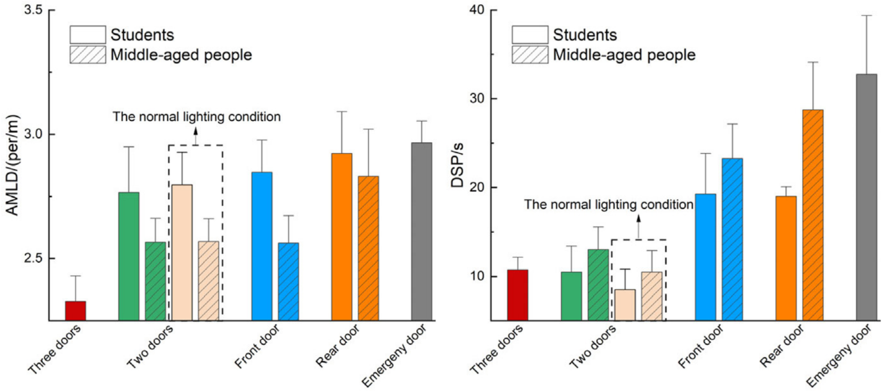


Fig. 9. The CLD in different evacuation scenarios.

lighting condition lead to increasing crowdedness (CLD) for both young students and middle-aged people. And, a higher level of crowdedness is found for the evacuation of middle-aged people, as compared to that of young students. To further understand the results of the CLD, Fig. 10 presents the corresponding AMLD and DSP. It can be seen that the evacuation with three doors available obtains the minimum AMLD. And, the AMLD slightly increases with the available exits varying from the two doors to only the emergency door. One possible explanation could be that when confronted with a longer waiting time, more and more passengers became impatient and thus rushed into the aisle. Interestingly, the AMLD of middle-aged people is observed to be significantly lower than that of young students in the experiments with the same setting (lighting and door availability), which implies that middle-aged people generally prefer to keep more space to others during evacuations. Furthermore, as expected, the DSP exhibits a similar changing trend as the CLD.

6. Discussion

The evacuation time and flow rate are conspicuously varied with the available exits in the present experiments, which is consistent with previous studies [9,14,20,30]. However, the measured average flow rates at the front door in the normal lighting condition for young students and middle-aged people, i.e., 0.91 per/s and 0.71 per/s, are found to be both much higher than those reported by Pollard et al. [14], i.e., 0.6 per/s. This could be attributed to the different settings of other influential factors, as described in the conceptual model. The results indicate that the evacuation efficiency (as for evacuation time and flow rate) significantly decreases and the crowdedness within the aisle increases in experiments with limited available exits as compared to the ideal conditions (i.e., all exits available). From this perspective, ensuring the usability/availability of exits (especially the cases with opening the front and rear doors that are observed to have a significantly higher flow rate compared with the case of only opening the emergency door) under emergency evacuations is critically important for the safety of passengers. This requires that the exit can be opened timely by passengers upon emergencies (based on the premise that it is mechanically openable [75]). Evacuation knowledge education and training for on-board passengers (by watching on-board TV, being instructed by drivers or conductors in each trip) may be helpful to improve evacuation performance. However, it is recommended that further concerns (e.g., the effect of training) need to be given on this issue.



(a) The AMLD (b) The DSP

Fig. 10. The AMLD and the DSP in different evacuation scenarios.

A previous small-scale study has shown that the flow rate significantly decreased on the stairways of the service door in the dim lighting condition (i.e., 0.2–0.6 lux) [30]. Similar results are found in our experiments. Generally, an average reduction of 0.14 per/s is observed for the flow rate of passengers in the dim lighting condition (less than 1 lux). These results suggest that it is important to have the emergency lighting system in high-deck coaches with regular nighttime operations, which could assist the evacuation when normal lighting devices malfunction at nighttime conditions in incidents. Although photoluminescent signage and instructions have been used on board to improve the conspicuity and visibility of emergency exits [76], to our best knowledge, no similar emergency lighting measure has been regulated for the floor and stairways in coaches in China yet. As suggested by Pollard et al. [30], high-performance photoluminescent (HPPL) path markings may become the practical and applicable scheme. However, its effectiveness and corresponding improvement on the evacuation will be the subject of our future research.

Another crucial issue that deserved particular concerns is the safe evacuation of middle-aged (and elderly) people, who are observed to have considerably longer pre-evacuation times and lower evacuation efficiency in the present experiments. Most middle-aged people were unwilling to participate in the experiments with emergency door evacuations (a 0.82-m height differential). It can be expected that middle-aged (and elderly) people would be confronted with much more difficulties in negotiating a 1.62-m difference in height when the emergency door evacuation is necessary in real emergencies. This may lead to a low successful evacuation rate and a high possibility of suffering from a secondary injury. Our results also show that the buffer stairs in the front door stairways (as shown in Appendix) do not significantly accelerate the evacuation of middle-aged people. Therefore, given the physical ability of middle-aged (and elderly) people, it is suggested that for high-deck coaches with a length equal to or more than 12 m a lower floor height should be designed. Furthermore, considerable differences in the evacuation behaviour of young students and middle-aged people highlight that it is important to consider the heterogeneity (e.g., age) of passenger groups in the simulation models intended to simulate generic passengers' evacuations.

7. Conclusion

A theoretically conceptual model has been proposed to capture the evacuation behaviour of coach passengers, based on which the effect of available exits, lighting conditions and age groups on the evacuation behaviour from a high-deck coach was investigated via controlled experiments. Specifically, data collection and analyses with respect to four performance indicators in the evacuation process, i.e., evacuation time, pre-evacuation time, flow rate and crowdedness, were conducted.

Our experimental results demonstrate the cause–effect relationships between three independent variables and four performance indicators, described in the conceptual model. Specifically, the results indicate that the evacuation efficiency significantly decreases, and the crowdedness significantly increases in evacuations with limited available exits for both young students and middle-aged people. Secondly, the dim lighting condition (less than 1 lux) is found to significantly prolong the evacuation and accordingly increase the crowdedness within the aisle regardless of the age groups. Thirdly, there exist prominent distinctions in pre-evacuation and en-evacuation movement behaviours between young students and middle-aged people. The evacuation of middle-aged people is observed to have a significantly longer pre-evacuation time, lower evacuation efficiency, and higher level of crowdedness. Furthermore, it is found that young students' pre-evacuation times conform to the Weibull distribution, whereas middle-aged people' pre-evacuation times could be well represented with the Loglogistic distribution.

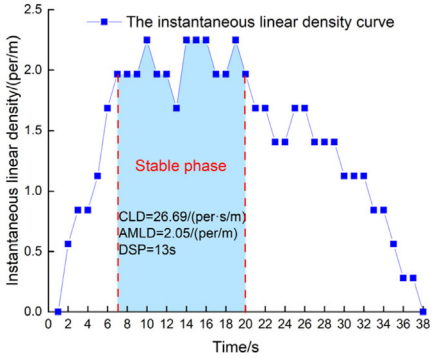
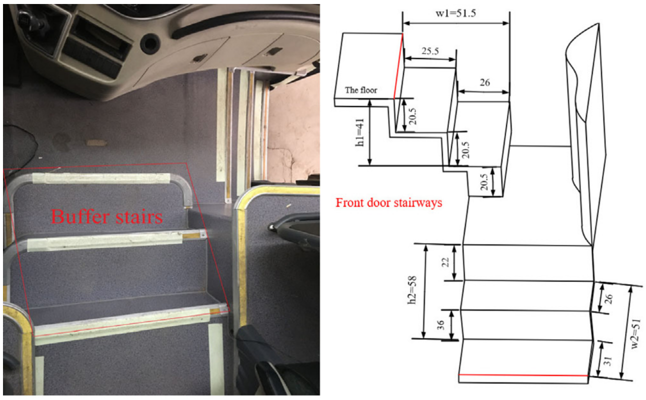
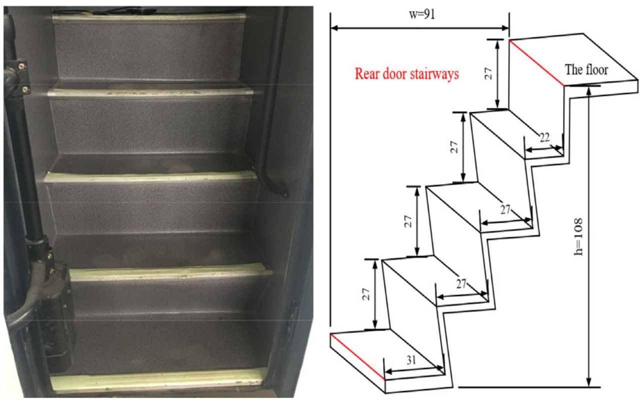


Fig. A.1. An example of the calculation of the CLD, the AMLD and the DSP.



(a) Front door stairways (top view) (b) Detailed dimensions (unit: cm)



(c) Rear door stairways (front view) (d) Detailed dimensions (unit: cm)

Fig. A.2. The configuration of stairways of the front and rear doors.

The present study suggests that effective measures should be implemented by high-deck coach designers and management authorities to improve the evacuation performance of high-deck coaches (with a length equal to or more than 12 m). Some practicably feasible measures may involve: (a) conducting evacuation knowledge education and training for on-board passengers (by watching on-board TV, being instructed by drivers or conductors in each trip) to ensure the usability/availability of exits (especially the front and rear doors), (b) equipping the floor and stairways with emergency lighting devices (e.g., high-performance photoluminescent (HPPL) path markings) to assist the evacuation in the dim lighting condition (less than 1 lux), and (c) decreasing the floor height to alleviate the evacuation difficulties of middle-aged (and elderly) people, especially in evacuations with only the emergency door available. Also, consideration of the heterogeneity (e.g., age) of passenger groups is crucial in the development of coach evacuation models aimed at reproducing generic passengers' evacuation behaviour, and the evacuation behaviour of a mixed-age population should be investigated. While this paper gives some critical insights on the evacuation behaviour from a high-deck coach, it must be recognized that the evacuation process from a high-deck coach is complex and affected by many other factors, as suggested in the conceptual model. Further studies need to be devoted to this topic. In addition, the pre-evacuation time and flow rate distribution data-sets could be used for the validation and calibration of coach simulation models and as empirical inputs by safety engineers in the evacuation performance assessment of transport facilities involving high-deck coaches, e.g., highway tunnels.

CRediT authorship contribution statement

Rong Huang: Study conception and design, Data collection, Analysis and interpretation of results. **Xuan Zhao:** Study conception and design, Data collection. **Yufei Yuan:** Analysis and interpretation of results, Comment to draft and revised manuscript. **Qiang Yu:** Study conception and design. **Chenyu Zhou:** Data collection. **Winnie Daamen:** Analysis and interpretation of results, Comment to draft and revised manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

As shown in Fig. A.1, the blue integration area between the instantaneous linear density curve and the X-axis was calculated as the CLD. The average density in the stable phase (e.g., between 7∼20 s in Fig. A.1) was calculated as the AMLD, and the DSP for this example is 13 s.

As shown in Fig. A.2, the front door stairways are generally less steep than the rear door stairways due to the existence of the buffer stairs (one kind of structure designed to alleviate the slope of the stairways). Thus, in the young student group, a higher flow rate for the front door than the rear door may be attributed to such a design.

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