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# Open Experimental Data-Sets to Reveal Behavioural Insights of High-Deck Coach Evacuations

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**Abstract.** Numerous evacuation performance data for the utilization in evacuation modelling and simulations have been established for the conventional/widely studied scenarios, such as building evacuation scenarios. However, such data are typically scarce for a new scenario in literature — evacuation from high-deck coaches. This paper fulfills this gap by presenting empirical high-deck coach evacuation data-sets that can be used for model configuration and validation. To this end, firstly, five essential and commonly used performance metrics, i.e., evacuation time, flow rate, alighting time gap, velocity on stairways and exit choice, were collected and derived from two series of controlled experiments with 7 and 22 runs that involved 44 and 96 participants respectively. Then, all these datasets were structured in the distribution form, based on which three critical behavioural insights are revealed regardless of the evacuation conditions (the types of high-deck coaches, lighting conditions, and age groups). First, the evacuation behaviour in normal (experimental) conditions conforms to a multi-stage pattern (a modified four-stage pattern, i.e., reaction, acceleration, fluctuation and saturation stages). Second, the instantaneous flow rate can be well captured by the Burr, Loglogistic and Lognormal distributions, and the alighting time gap can be represented by the Burr distribution. Third, more than 50% of passengers evacuate through the rear door in the front-and-rear-door evacuations. The frequency of choosing the front door is found to shift towards the direction of the rear door compared to the ideal results (based on the shortest distance calculation) with a magnitude of approximately 1.95 seat rows. The presented data-sets are valuable resources for the development of high-deck coach evacuation models. The empirical findings promote the understanding upon the evacuation behaviour of high-deck coach passengers.

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**Keywords:** High-deck coaches, Data-sets, Evacuation behavior, Modelling and simulation, Distribution

## 1. Introduction

Evacuation behaviour modelling and simulations are crucial in the performance-based design of pedestrian/passenger facilities [1]. As such, numerous pedestrian simulation models, such as the social force model [2], the network model [3], the grid model [4], the agent-based model [5] and other continuum models [6, 7], have been developed to simulate crowd evacuations. By applying these general models, evacuation behaviour of occupants/passengers has been modelled and studied in specific scenarios, including buildings [8, 9], public facilities [10–12], and transport vehicles [13–15]. However, there are also some new scenarios where pedestrian modelling and simulations have not been well established and/or validated [16]. To the best of our knowledge, the empirical data-set dedicated to high-deck coach evacuation behaviour modelling and simulation is absent in literature, as discussed in Sect. 2 (Literature review), and thus it can be viewed as one of the typical new scenarios.

Characterized by a two-deck structure (the upper deck for accommodating passengers and the lower deck for serving as the baggage compartment), high-deck coaches (also referred to as “over-the-road” buses or motorcoaches) differ from transit buses and school buses. The latter vehicle types are equipped with one single deck as the passenger carriage floor with the purpose of lowering the floor height (usually no more than three steps [17]) [18], to increase the evacuation efficiency. In many countries, high-deck coaches have become one of the major modes for long distance travel. However, they were also reported to bring severe consequences in accidents (e.g., high-deck coach accidents resulted in 442 casualties from 2015 to 2017 in China [19]). This could be partially ascribed to the physical configuration of high-deck coaches, which are characterized by the steep stairway, the narrow aisle and the dense seat row. These structures have been demonstrated to be the significant influential factors in evacuations in the context of buildings (the steep stairway [20]) and trains (the narrow aisle [21] and the dense seat row [22]). And, they are expected to further deteriorate the evacuation efficiency of high-deck coach passengers due to the extreme dimensions of these structures in high-deck coaches (e.g., the maximum riser of the stairs regulated in China is 150 cm in buildings [23], whereas this value increases to 250–430 cm in high-deck coaches [24]). It is thus urgent and valuable for operation managers and/or authorities to ensure efficient and safe evacuations of high-deck coach passengers in case of emergencies. To this end, validated and calibrated models and simulation packages are imperative to assess potential precautions and mitigation strategies.

Moreover, it has been a growing consensus that mathematical models pertaining to evacuation behaviour should be validated and calibrated by empirical data [25–28]. Besides, evacuation performance indicators can provide significant support for decision-making in evacuation management [29, 30]. Furthermore, evacuation data can serve as the basis of the formulation of safety regulations,

guidelines and standards [30]. Therefore, it is of particular importance and urgency to collect and present evacuation performance data-sets in the context of high-deck coaches.

Although field observations could obtain unbiased behavioural data, raw videos recording the emergency evacuation process of passengers and/or detailed individual characteristics are commonly unavailable [28, 31]. Moreover, evacuation drills could also suffer from significant challenges, such as the repetition of observations [31]. Thus, with a reasonable balance between realism and controllability, laboratory experiments are preferable given the purpose of this research topic [28, 32–35].

This paper aims to provide empirical data-sets and behavioural insights that can help in configuring and validating the models that intend to simulate high-deck coach evacuations. The main contributions of this paper are listed as follows. First, this paper, for the first time, presents empirical high-deck coach evacuation data-sets that can be used for model configuration and validation, which were collected from two series of independent controlled experiments. The data regarding one series of the experiments are recorded in the spreadsheet and made available online (see supplementary material S1) for interested researchers. Second, a multi-stage pattern (a modified four-stage pattern, i.e., reaction, acceleration, fluctuation and saturation stages, or its variants of two/three stages) is developed to delineate passenger evacuation behaviour in a high-deck coach under normal (experimental) conditions. Third, through statistical comparisons of five candidate distributions, this paper respectively identifies the best-performance distribution(s) in capturing the distribution characteristics of the instantaneous flow rate and the alighting time gap. Forth, important characteristics of the exit-choice behaviour and the exit-choice changing behaviour in multi-exit high-deck coach evacuations are disclosed. It should be noted that the two series of experiments have been reported in Zhang et al. [36] and Huang et al. [37], but this is for the first time that the data and the analyses are presented and discussed in this way, with an exception that the descriptive information of the flow rate samples from one series of the experiments have been presented in Huang et al. [37].

The remainder of this paper starts with a literature review on the evacuation from high-deck coaches and the research gaps, followed by the methodology and the experimental context in Sect. 3. Then, data collection and analysis are presented in Sect. 4. This is followed by the corresponding results in Sect. 5. A discussion on the potential application of the proposed data-sets is presented in Sect. 6, and the final conclusion and recommendations are given in Sect. 7.

## **2. Literature Review**

This section first reviews the experimental efforts dedicated to the evacuation from high-deck coaches and other transport vehicles and then considers the methodologies to resolve the data variability related to behavioural uncertainty in experimental and simulation studies.

### 2.1. Experimental studies on evacuations from high-deck coaches

On the evacuation behaviour from a high-deck coach, a great deal of experiments have been performed, summarized in Table 1. It should be noted that the experiment using an exactly or a nearly fully-loaded (with usually only one or two seats vacant) high-deck coach is identified as the *full-scale experiment*; otherwise (here lower than the 50% capacity, summarized from the studies in Table 1), it is refer-

**Table 1**  
**Literature Review of Experimental Studies on the Evacuation from High-Deck Coaches**

No	Country and source	Experiment Type	Facility	Testing exits	Performance indicators
1	America [38]	Small-scale	Mockup	Emergency window	Individual passing time
2	America [39]	Full-scale	Real coach	Emergency window, emergency door, front door	Total evacuation time, average flow rate
3	UK [41]	Small-scale	Mockup	Emergency window	Individual passing time
4	UK [41]	Full-scale	Real coach	Emergency door, emergency window	Total evacuation time
5	America [40]	Full-scale	Real coach	Emergency window, front door, roof hatch	Total evacuation time, average flow rate
6	Germany [41]	Full-scale	Real coach	Front and rear doors, emergency window	Total evacuation time
7	Japan [41]	Small-scale	Real coach	Front door, emergency door, emergency window	Individual evacuation time
8	Hungary [41]	Full-scale	Real coach	Emergency window, front and rear doors, emergency door	Total evacuation time
9	Hungary [41]	Small-scale	Real coach	Emergency window	Individual evacuation time
10	America [17]	Full-scale; Small-scale	Real coach	Front door; emergency window, wheelchair-access door, roof hatch	Total evacuation time, average flow rate
11	America [45]	Small-scale	Mockup	Wheelchair-access door, service door	Average flow rate
12	China [36, 37]	Full-scale	Real coach	Front door, rear door, emergency door, front and rear doors, three doors	Total evacuation time, average flow rate
13	Australia [42]	Small-scale	Real coach	Front door	Individual evacuation time
14	China (Taiwan) [44]	Small-scale	Real coach	Front door, rear door, emergency door	Alighting Time gap

(NB: only experiments of which the collected data-sets have been published and/or reported are included in Table 1)

red to as the *small-scale experiment* in this paper. In literature, most of the experiments focused on evaluating the evacuation performance of a high-deck coach, and thus different evacuation situations have been considered and tested using the mockup or the real high-deck coach by researchers from different countries, including America [17, 38–40], UK [41], Germany [41], Japan [41], Hungary [41], and China [36, 37]. Apart from this topic (i.e., evaluating the evacuation performance), Melis et al. [42] validated the ability of Pathfinder [43] to simulate the evacuation within the narrow seat aisle by three small-scale high-deck coach evacuation experiments, and Chung et al. [44] studied the alighting time gap distribution characteristics of high-deck coach passengers.

Except the studies of Melis et al. [42] and Chung et al. [44] with additional attentions, existing studies focused on either the total evacuation time/the average flow rate of a fully-loaded high-deck coach when certain emergency exits were available, or even on the individual passing/evacuation time from certain emergency exits by small-scale experiments (as studies in America [38], UK [41] (No. 3), Japan [41] and Hungary [41] (No. 9)). The total evacuation time and the average flow rate were derived through the measurement by the full-scale experiments (as studies in America [17, 39, 40], UK [41] (No. 4), Germany [41], Hungary [41] (No. 8), China [36, 37]), or the estimation by the quantities obtained from the small-scale experiments (as studies in America [17, 45]). On one hand, the results derived from the small-scale experiments are likely to be considerably poor for representing the realistic high-deck coach evacuations, since the evacuation process is significantly influenced by the individual interactions [46]. On the other hand, only the final/average evacuation outcomes (i.e., single-value outcomes: the total evacuation time/the average flow rate) were presented for the full-scale experiments in literature, which cannot reflect the dynamics of the whole evacuation process [47] and thus could lead to biased results when used for model configuration and validation. Currently, researchers commonly use the data that include the process information (e.g., the evacuation time curve as in Galea et al. [21], and the flow rate distribution as in Yao and Lu [30]) to calibrate and validate evacuation models. However, these evacuation performance data are absent for high-deck coaches in literature, which slows down the development of specialized evacuation models and in turn hinders the further understanding upon the evacuation process from this scenario.

## 2.2. Experimental Studies on Evacuations from Other Transport Vehicles

Studies have also reported on evacuations from other transport vehicles, including transit buses, school buses, aircrafts, trains and passenger ships, by means of experiment. Liang et al. [48] collected the total evacuation times of an electronic transit bus when the front door, the rear door, and the front and rear doors were opened. Due to the limited cognitive and physical abilities of children, the evacuation performance of school buses has attracted extensive attention from 1970. The National Highway Transportation Administration (NHTSA) organized a series of experiments to investigate the potential impact of various evacuation conditions, including the combination of available exits, visibility, orientation (upright or rol-

led-over), and the size of a roof hatch in 1970 and 1972 [38, 39]. Then the stagnation of research on this topic has continued for several decades, which is broken by a study that analyzed the evacuation process of students in a school bus after a severe accident using on-board video recordings [49]. Recently, to re-examine the efficacy of the emergency evacuation system in school buses, Abulhassan et al., [50, 51] measured the evacuation performance of young children (no more than third grade) from a school bus in the upright and rolled-over orientations and suggested that children in kindergarten through second grade lack sufficient physical capabilities to operate the rear emergency door. According to these findings, Gunter et al., [52, 53] improved the design of the rear emergency door hold-open device and the roof hatch so as to increase the evacuation efficiency, which is demonstrated via egress experiments.

In contrast to the lack of eligible data-sets for configuring and validating high-deck coach evacuation models, specific experimental data-sets dedicated to evacuation modelling exist for aircrafts [54], trains [15, 21] and passenger ships [55], based on which corresponding specialized evacuation models have been developed and validated. However, to the best of our knowledge, no similar validated specialized evacuation model exists for high-deck coaches, which hinders the manufacturers from performing the “Performance-Based Design” [1] to improve the evacuation performance.

### ***2.3. Treatment of Behavioural Uncertainty***

Human behaviour is inherently stochastic, and thus behavioural uncertainty that is one of the significant sources of the data variability should be considered in formulating experimental data-sets and evacuation models [56]. The empirical study on the variability associated with behavioural uncertainty requires multiple empirical data-sets for an individual evacuation scenario [57], which makes it quite difficult due to the high resource consumption (e.g., cost and time) for data collection. And thus there is usually a sole empirical data-set available for a specific scenario [47]. Ascribed to the relatively light resource demand of the evacuation modelling, assessing the variability of the simulation results induced by behavioural uncertainty has gradually become a consensus for a proper model validation. Galea et al. [58] first proposed a validation procedure including three convergence criteria based on functional analysis [59] to consider uncertainties of the empirical data-set. Then, Ronchi et al., [47] introduced a methodology to determine the optimal number of the repeated runs when the evacuation times in the simulation models converge. And, Smedberg et al., [60] further improved it by incorporating the assessment of the variance of other factors (e.g., flow rate) related to evacuation dynamics. In the light of the variability of empirical data, Lovreglio et al., [61] proposed a protocol to validate evacuation models, which simultaneously considers behavioural uncertainty stemming from experiments and simulations. However, the lack of multiple (more than three) empirical data-sets for a specific scenario limits its application.

To incorporate the stochasticity of behaviour in evacuation modelling, researchers have commonly used probability distributions as model inputs and outputs

[15, 62–64]. This requires that the empirical data-sets intended to be used for model configuration and validation are structured in the distribution form. Therefore, in different occupant/passenger facilities (e.g., buildings and transport vehicles), empirical distributions of commonly used evacuation performance indicators, such as evacuation time [62, 65], flow rate [37], alighting time gap [44], velocity [15, 62, 66], and exit choice [65], have been proposed and/or used for evacuation modelling.

### **3. Summary**

This review clearly indicates the importance of evacuation performance data-sets that can be used to configure and validate the models that intend to recreate the high-deck coach evacuation scenarios. And, there is no such a dataset in literature (to the authors' best knowledge). Furthermore, it also suggests that the data-sets should be structured in the distribution form so that the study of behavioural uncertainty can be possible in evacuation modelling.

### **4. Methodology and Experimental Context**

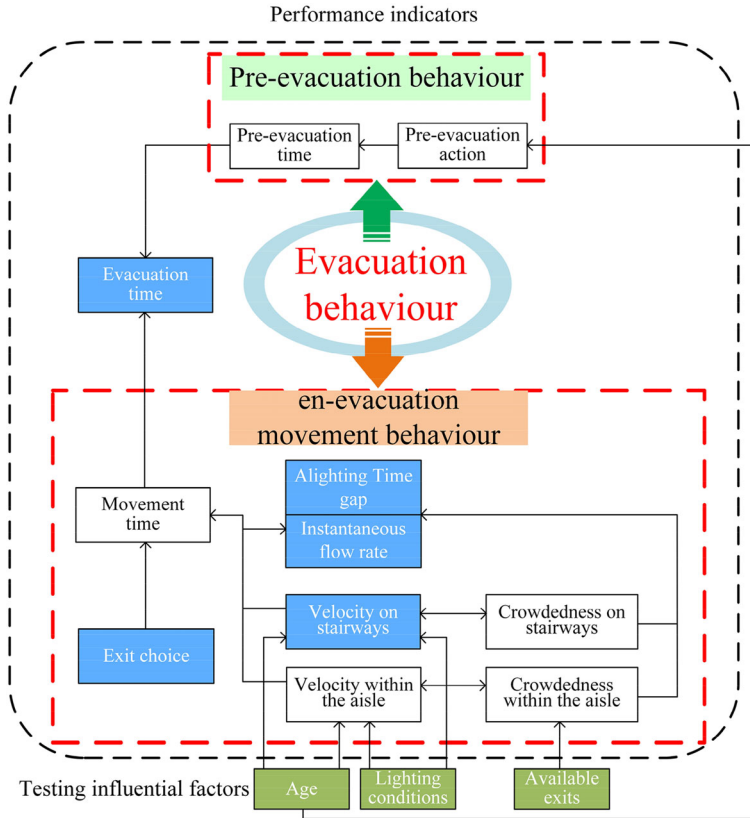
This section introduces detailed information about the two series of independent controlled experiments used to collect the evacuation performance data-sets, which could help potential users to understand the context of data collection and determine how and where to utilize the data-sets.

#### **4.1. Scenarios**

In case of real emergencies, two kinds of evacuation situations, i.e., the free or hindered flow situations, can be divided for high-deck coach evacuations according to whether there is any barrier (e.g., other vehicles, rails, etc.) outside the doors to restrict the exiting process of passengers. In this respect, two series of independent experiments presented in this paper are complementary each other, though the context, including the types of high-deck coaches, the participants, and the experimental schemes, are different for them. The context information will also be provided to help interested third parties configure the simulation models according to the evacuation situation (i.e., the free or hindered flow situations) that they intend to reproduce.

The conceptual framework elaborating on the performance indicators and the testing influential factors of these two series of experiments is shown in Figure. 1 [37]. According to the engineering timeline, the evacuation behaviour consists of the pre-evacuation behaviour and the en-evacuation movement behaviour [37]. The prefix “en” is used to highlight that the described movement behaviour occurs during evacuations, so on the way to the exit (not for other purposes, e.g., collect the luggage). The pre-evacuation behaviour can be described by the pre-evacuation action and time, and the latter as the final outcome is usually used to quantify this process. As for the en-evacuation movement process, the perfor-





**Figure 1. Conceptual modelling framework on the performance indicators and the testing influential factors of the experiments presented in this paper. The connections are depicted by the arrowed lines.**

mance indicators mainly include the movement time, the flow rate/time gap, the velocity (within the aisle or on the stairways), the crowdedness (within the aisle or on the stairways) and the exit choice, some of which are theoretically interrelated. Specifically, the movement time depends on the velocity and the exit choice, and the flow rate/time gap is also influenced by two interactional performance indicators, i.e., the velocity and the crowdedness. The cause-effect relationships between the performance indicators and the influential factors presented in Figure. 1 have been demonstrated in Zhang et al. [36] and Huang et al. [37]. Specifically, Zhang et al. [36] studied the effect of available exits, exit widths, passenger load and driver's assistance on the evacuation, and Huang et al. [37] explored the cause-effect relationship between available exits, lighting conditions, age groups and evacuation behaviour.

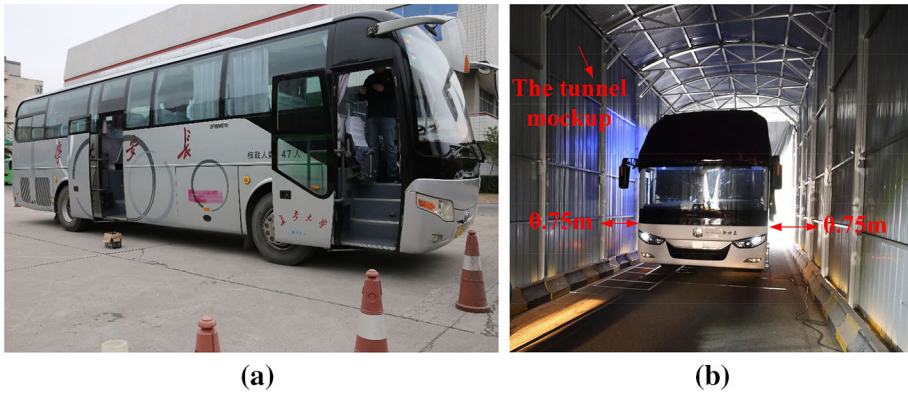
In this paper, five essential and commonly used performance indicators colored in blue will be discussed. Other performance indicators in Figure. 1 either cannot

be obtained by manual data extraction (the movement time, the velocity within the aisle) or have been presented in our previous studies (e.g., the pre-evacuation time in Huang et al. [37]). The crowdedness on the stairways is quantified by the linear density here, which is used to further classify the velocity on the stairways. It should be noted that the videos recording the evacuation process from the experimental high-deck coaches are processed by manual frame-by-frame analysis due to the constraints of the confined space (the low height from the floor to the ceiling (less than 1.80 m) and the narrow width (less than 2.5 m)) and the dense obstacles (e.g., the seat rows, the luggage rack, etc.) within the carriage, which make it rather difficult to accurately automatically trace the evacuation process and participant trajectories.

Seven experiment runs (denoted as series A) from Zhang et al. [36] simulated the free flow evacuation situation in an open area using a type of high-deck coach (denoted as A), with a mixed age group of participants, while the 22 experiment runs (denoted as series B) from Huang et al. [37] were conducted under the hindered flow situation in a tunnel mockup using another type of high-deck coach (denoted as B), with a group of young students and middle-aged people. These experiments together constitute 13 scenarios involving different evacuation conditions, i.e., high-deck coach A/B, varying available exits, the normal/dim lighting condition, and the mixed age group/young students/middle-aged people, as illustrated in Table 2. It should be noted that available exits, lighting conditions and

**Table 2**  
**The Included Experimental Scenarios**

External environment	Series	Scenarios	Runs	Available exits	Age Groups	Lighting conditions
Open area	A	1	5	Front and rear doors	Mixed age group	Normal
		2	1	Front door	Mixed age group	Normal
		3	1	Rear door	Mixed age group	Normal
Tunnel mockup	B	4	2	Three doors	Young students	Dim
		5	2	Front and rear doors	Young students	Dim
		6	2	Front door	Young students	Dim
		7	2	Rear door	Young students	Dim
		8	2	Emergency door	Young students	Dim
		9	2	Front and rear doors	Middle-aged people	Dim
		10	2	Front door	Middle-aged people	Dim
		11	2	Rear door	Middle-aged people	Dim
		12	3	Front and rear doors	Middle-aged people	Normal
		13	3	Front and rear doors	Young students	Normal



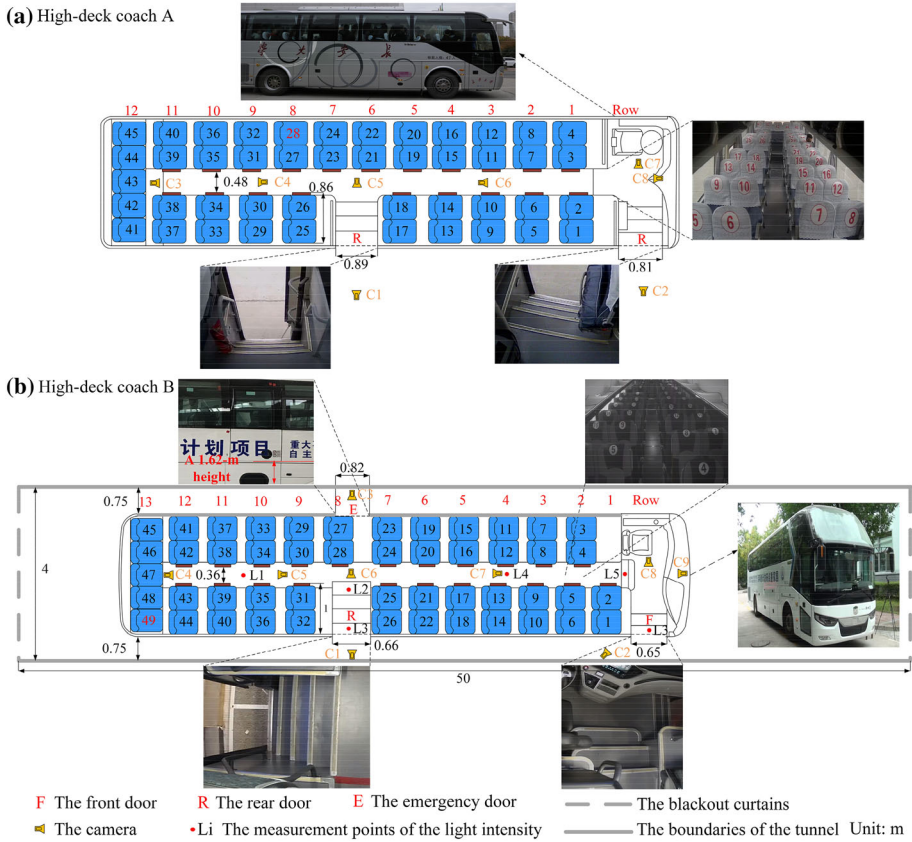
**Figure 2. The evacuation situations of series A and B experiments ((a): the free flow situation, (b): the restricted flow situation).**

age groups are three variables significantly influencing passengers' evacuation [36, 37]. Detailed information for the experimental scheme can be referred to Zhang et al. [36] and Huang et al. [37], which is out of the scope of this paper. It should be noted that the two series of experiments both only involve the evacuation through available doors, which is the common and representative high-deck coach evacuation scenario. This is because it is actually difficult or even unlikely for passengers to break the emergency windows in time under emergencies [67], and the usability of the emergency windows and roof hatches are low when the high-deck coach is standing on its wheels [68].

Though the data-sets cover many evacuation scenarios in the high-deck coach, some evacuation conditions are coupled together (e.g., the free flow situation and the mixed age group). It means that if one wants to recreate the evacuation under a specific condition, he/she also needs to configure its coupled condition(s). However, this has little effect on the application and generalization of our data-sets, as the detailed context information of the experiments is also presented, besides the data and the behavioural insights (Figure. 2).

#### 4.2. Layouts

As shown in Figure. 3, high-deck coach A is equipped with the front and rear doors, while high-deck coach B has an additional emergency door, the door sill of which is 1.62 m above the ground. These two kinds of emergency evacuation systems (i.e., with or without the emergency door) currently both exist in China [24]. Besides, there are considerable differences in the internal layout of high-deck coaches A and B. For instance, 45 seats are arranged as 12 seat rows in high-deck coach A, while the passenger capacity of high-deck coach B is 49 (13 seat rows). To accommodate the video equipment, one of the seats (i.e., numbers 28 and 49 seats, colored in red) was not used in series A and B experiments respectively. Eight and nine cameras were installed to record the evacuation process of passengers, respectively.



**Figure 3. The layout of the experimental high-deck coaches and the video cameras' location.**

In series B experiments, the dim lighting condition corresponds to the average light intensities ranging from 0.29 lx to 0.85 lx, measured in six locations (L1-L6) before and after the experiments. This lighting level basically satisfies the illumination level of “nigh-lights” suggested by Pollard et al. [45], i.e., 0.1–0.8 lx.

### 4.3. Participants

A group of 44 passengers consisting of 27 males (61.4%) and 17 females (38.6%), aged from 20 to 68 years, was recruited to perform series A experiments. For series B experiments, both the young student and middle-aged people groups were composed of 28 males (58.3%) and 20 females (41.7%). The young students were aged between 20 and 23 years, with average years of 21.4. For the middle-aged people group, their age ranged from 41 to 65 years, with average years of 52.4.

As most of the participants were reported to ride the high-deck coach 1 to 4 times or more per year, they could be regarded as potential high-deck coach passengers, at least, to some degree. And, they all had not experienced real or simu-

lated coach evacuation drills, which lays a solid foundation for the credibility and validity of our data-sets.

#### **4.4. Procedures**

Series A and B experiments have basically identical procedures. After signing the consensus agreement for the voluntary involvement of the experiments, participants were instructed to determine when and how to evacuate the high-deck coach through available doors independently during the experiments.

Measures were implemented to ease the effect of learning behaviour and fatigue. Specifically, each participant was randomly allocated to different seats in different experiment runs, and a short break (3–5 min) was set between two consecutive experiment runs. After all participants sat in their seats, the driver kept the engine idling to simulate the normal driving condition. To simulate the real accident situation as much as possible in our experiments, pre-recorded high-pitched voices extracted from a real-life accident (i.e., brakes screeching mixed with glasses shattered) were used as the emergency signals. They were played out at a random time (in 2–3 min) by the on-board broadcast system which includes several loudspeakers distributed in the ceiling, and the sound volume was adjusted to ensure that each passenger can clearly hear the signals. Thereafter, the driver just stalled the engine without giving any other information. Participants exiting the coach would be led to a specific area until an experimental case finished.

It should be noted that the participants in series A experiments had to manually operate the emergency device to open the available exits, whereas they remained open throughout series B experiments. Opening the exits manually will result in an additional time delay for the evacuation of passengers. The effect of such a time delay on the model configuration and validation could be trivial, because it plays no role on the interactions between passengers in evacuations, but it will translate the evacuation time curve along the coordinate axis towards the right (higher evacuation times). However, it does not influence other performance indicators (e.g., flow rate). In the experiments under the dim lighting condition, effective measures, including turning off the lights inside the coach and pulling down the blackout curtains, were implemented to achieve the required night-light level. Moreover, the emergency door experiments were conducted with outside a desk having a height of 0.8 m due to safety reasons.

### **5. Data Collection and Analysis Process**

Through manual frame-by-frame analysis, five performance indicators were extracted from the videos recording the experiments at the frame rate of 25 per second. As aforementioned, data of the five performance indicators would be further classified according to the evacuation conditions (i.e., high-deck coach A/B, varying available exits, the normal/dim lighting condition, and the mixed age group/young students/middle-aged people), which allows researchers to flexibly choose the evacuation performance data based on the condition that they intend to study. Then, some behavioural insights were revealed by the data analyses.

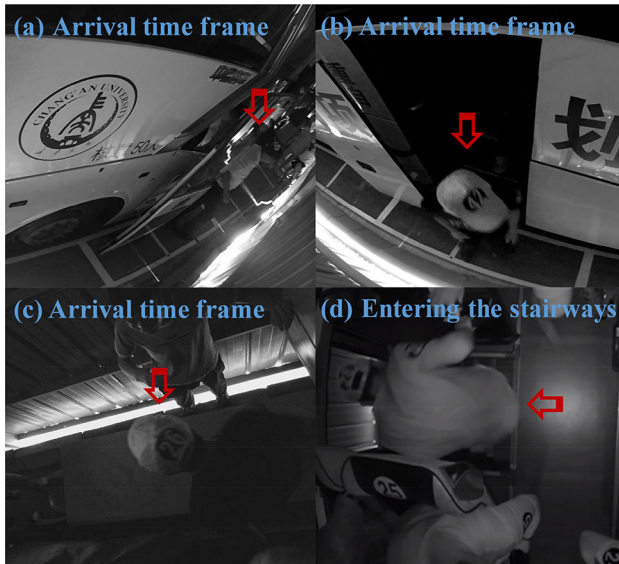
### 5.1. Evacuation Time

The evacuation time of each passenger was determined by extracting the time frame when his/her both feet landed at the ground or desk [69], as shown in Figure. 4a–c. Then, 13 evacuation time curves and evacuation time histogram distributions were generated according to the different evacuation conditions. With the cumulative curve of departures and the number of evacuated passengers per two seconds, a modified multi-stage pattern will be proposed to describe the evacuation behaviour of passengers.

### 5.2. Flow rate

There are two approaches to represent the flow rate of occupants/passengers, i.e., deterministic [34] or probabilistic approaches [70]. As the latter can incorporate the personal hesitations or limitations in the exiting performance [70], the instantaneous flow rate distribution is used in this paper. Correspondingly, the instantaneous flow rate is defined as follows [70].

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



**Figure 4.** An example of the time frame extraction (snapshots (a), (b), (c) and (d) were from cameras C1, C2, C3 and C4 in series B experiments, 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 snapshot (d), passenger 28 entered the rear door stairways.

where  $F_c$  is the instantaneous flow rate,  $\Delta G(i, i - 1)$  is the arrival frame difference between the two passengers consecutively evacuating,  $f$  is the frame rate.

Similarly, the collected flow data-sets were divided according to the evacuation conditions. Thus, 3 and 14 flow samples were obtained from series A and B experiments respectively based on the assumption that the exiting processes through different doors are mutually independent [37]. Moreover, the adjusted boxplot considering the med couple was used to clear the outliers from the flow samples [69].

To estimate the probabilistic distribution of these instantaneous flow rate samples, four two-parameter distributions, i.e., Gamma, Loglogistic, Lognormal and Weibull, and the three-parameter burr distribution were considered. These five candidate distributions were estimated as they are only defined in the positive domain and can reflect the skewed characteristics of flow distributions and widely used in traffic and pedestrian flow fields [71, 72]. The maximum likelihood estimation method was used to properly estimate the parameters of these distributions for each flow sample [73]. To determine the distribution form with the superior fitting performance for the flow rate data-sets under different evacuation conditions, the Chi-square value was calculated to assess each estimation [74], and also the Chi-square test was conducted to identify the estimated distribution with statistical significance.

### 5.3. Alighting Time Gap

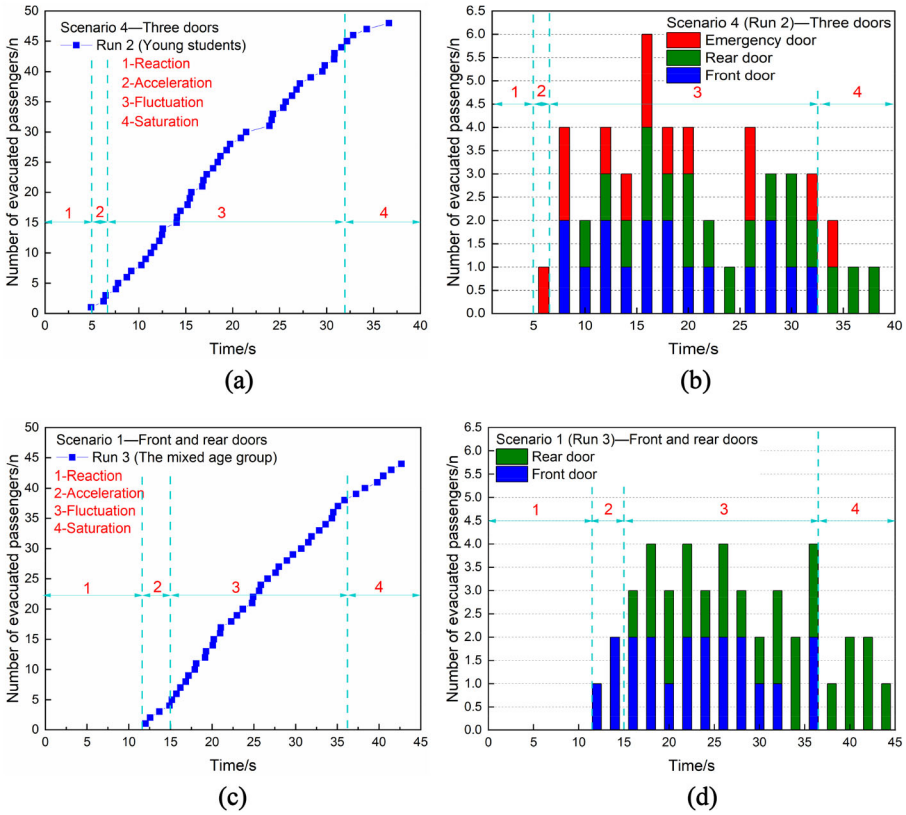
The alighting time gap is defined as the time interval between two consecutive evacuated passengers in this paper [44]. According to the different evacuation conditions mentioned above, 11 alighting time gap samples were classified for researchers to conveniently choose the one that closely fits their intentions. For each alighting time gap sample, the five candidate distributions (illustrated in Sect. 4.2) were also estimated and assessed to identify the one that well describes the distribution characteristics of the alighting time gap samples in different evacuation conditions.

### 5.4. Velocity on stairways

The evacuee velocities on stairways of the front and rear doors were collected. By the field measurement, the covered distances between reference lines 1 and 2 are 1.06 m and 1.19 m for the stairways in high-deck coach A, and those in high-deck coach B are 2.31 m and 1.41 m, as shown in Figure. 5. It should be noted that the tread and the riser of a step may not be mutually perpendicular for the stairways in high-deck coaches (e.g., as presented in Figure. 5b), on which particular attention should be paid in the modelling process.

Then, the velocity of each evacuee was calculated by Eq. (2):

$$v = \frac{L}{(F_e - F_o)/f} \quad (2)$$



**Figure 5. The covered distance of the stairways in high-deck coaches A and B.**

where  $v$  is the evacuee velocity (in m/s),  $L$  is the covered distance of stairways (in m).  $F_e$  is the time frame when the body of a passenger enters the stairways by crossing reference line 1 shown in Figure. 4d, and  $F_o$  is the time frame when the body of a passenger exits the stairways, which was approximated by the arrival time frame. This may result in minor errors in the velocity data-sets.

Similarly, the velocity data-sets were divided as 10 velocity samples. And, the linear density was measured to further classify the velocity within each sample, defined as in Eq. (3) [75].

$$d = \frac{N}{L} \tag{3}$$

where  $d$  is the linear density (in per/m),  $N$  is the number of passengers who are already on the stairways when the targeted passenger who is observed for determining its velocity  $v$  enters into the stairways. This way, the defined variable measures the congestion in front of the targeted passenger when he/she traverses the



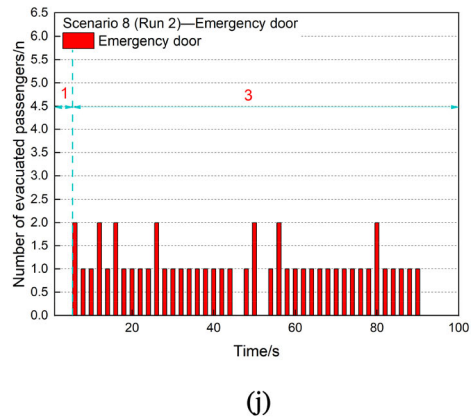
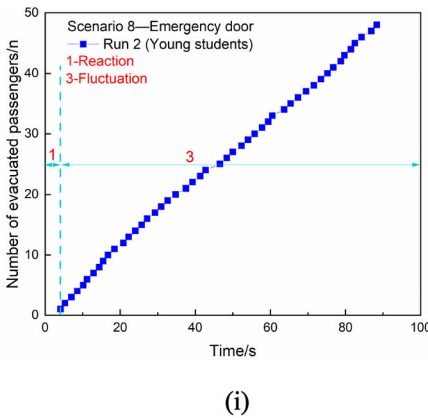
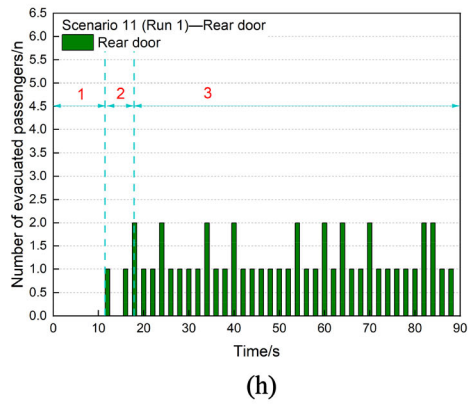
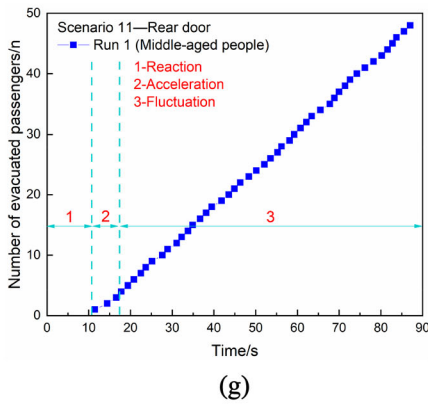
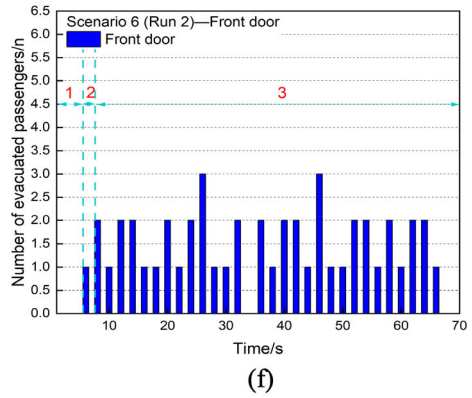
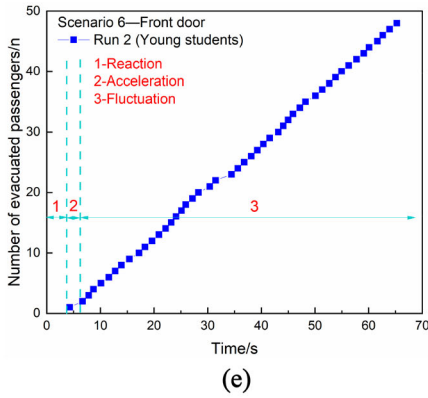


Figure 5. continued.

stairways, which impacts his/her movement. The significant advantage of this method is that the linear density can be straightforwardly calculated after collecting each passenger's time frame of entering and exiting the stairways in the process of determining the velocity, which avoids the laboriously manual count. It

should be noted that the obtained density could be zero, because the targeted passenger is not included in the density count [75]. While this method slightly differs from commonly used methods, this is expected to have no impact on configuring and validating models, because the same quantity can be calculated in simulations based on the aforementioned definition.

In addition, it should be noted that the time frame when the passenger crossed reference line 1 was hard to identify in some cases due to the congestion in front of the stairways. Thus, the velocity data within such congestion periods were discarded to ensure the accuracy of the data-set.

### 5.5. Exit Choice

The exit used by each passenger can be recognized from the video footage. The proportion distribution and the spatial distribution of the exit choice in the evacuations with multi-exit available is then obtained to reveal some common characteristics of the exit-choice behaviour and the exit-choice changing behaviour in series A and B experiments. This information is valuable for understanding the evacuation behaviour of passengers and the validation of evacuation models.

## 6. Summary

The collected data-sets consist of five performance indicators under different evacuation conditions, including:

- (1) Evacuation time: 13 evacuation time curves and evacuation time histogram distributions,
- (2) Flow rate: 17 instantaneous flow rate samples,
- (3) Alighting time gap: 11 alighting time gap samples,
- (4) Velocity on stairways: 10 velocity samples in the specific density range,
- (5) Exit choice: the proportion and spatial distributions of passengers evacuating through different available exits.

In addition, some behavioural insights regarding the evacuation behaviour, the distribution characteristics of the instantaneous flow rate and alighting time gap samples, the exit-choice behaviour and the exit-choice changing behaviour are provided to promote understanding upon the evacuation from this type of new scenario (high-deck coaches).

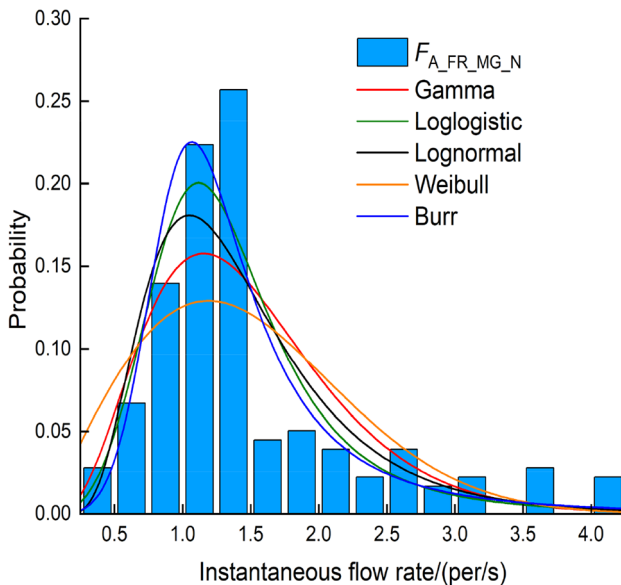
## 7. Results

In this section, the empirical data and behavioural insights pertaining to the five performance indicators will be presented. In addition, the raw data collected from series A experiments are also accessible in supplementary material S1. The interested third parties can use these data and the background information presented in this paper and in Zhang et al. [36] to configure or validate the high-deck coach evacuation models.

### 7.1. Evacuation Time

For the sake of simplicity, all the evacuation time curves and histogram distributions for series A and B experiments and corresponding data insights are presented in Figure A1 (in Appendix A).

There are five types of evacuation scenarios included in the data-sets (i.e., the evacuation with only the front door opened/only the rear door opened/only the emergency door opened/the front and rear doors opened/three doors opened), which can be further classified into multi-exit or single-exit evacuations according to the number of available exits. Then, following the methodology in Yang et al. [76] and Gu et al. [77], the evacuation time curve and the number of evacuated passengers per two seconds that can respectively describe the average speed and the dynamic evolution of the evacuation process are obtained and analyzed for each run to summarize the behaviour pattern of passengers in the multi-exit and single-exit evacuations. To save the volume of this paper, for each type of evacuation scenarios, only the results of one run were (arbitrarily) selected here to exemplify the observed behaviour pattern, as shown in Figure. 6. For the multi-exit evacuation scenarios, it can be seen that the nonlinearity of the cumulative curves is noticeable, which is demonstrated by the plots shown in Figure. 6a–d. Inspired by Yang et al. [76] and Gu et al. [77], a four-stage pattern comprised of *reaction*, *acceleration*, *fluctuation* and *saturation* stages, and its variants are developed to



**Figure 6. Statistical data on the examples (scenarios 4, 1, 6, 11 and 8) of evacuations with different available exits. The plots on the left and right show the cumulative number of evacuated passengers and the number of evacuated passengers per 2 s, respectively.**

describe passengers' evacuation behaviour in the multi-exit high-deck coach evacuations under normal (experimental) conditions.

- (1) *Reaction*. The cumulative curve starts with a reaction stage, at which the number of evacuated passengers remains at zero. This is slightly different from the reaction stage of occupants in building evacuations proposed by Gu et al. [77], which can be regarded as the pre-evacuation stage. In high-deck coach evacuations, in the situations when available exits remain closed at the beginning of evacuations (as in series A experiments) due to the factors induced by accidents (e.g., driver's incapability), this stage of the on-board passengers also includes a time delay resulting from manually operating the emergency device to open the exits. It should be noted that this time delay is a part of en-evacuation movement time, but not pre-evacuation time, because it occurs while evacuating.
- (2) *Acceleration*. Many passengers have finished the pre-evacuation actions and rushed to the available exits at this stage, resulting in a significant increase of the exit flow [76, 77]. It turns into the fluctuation stage after the maximum flow capacity of the available exits is reached. Due to the narrow width of the exit in high-deck coaches that only allows one passenger to pass at a time, the acceleration stage is related to the response of the on-board passengers at the beginning of evacuations and thus cannot be observed in the case of many passengers simultaneously responding to the evacuation and exiting the coach, because the exit flow capacity immediately saturates (i.e., runs 1 and 2 of scenario 9, runs 1 and 3 of scenario 13).
- (3) *Fluctuation*. At this stage, the cumulative curve does not increase absolutely linearly but has numerous irregular fluctuations, and correspondingly the number of evacuated passengers per two seconds fluctuates around the maximum flow capacity. This is mainly because the instantaneous flow rates of the exits are variable (as demonstrated in the descriptive statistics of the flow samples in Sect. 5.2), resulting from the joint effect of passengers (physical abilities, and behaviour) and the design of the exits and stairways [37]. This is different from the third (i.e., linearity) stage defined in Gu et al. [77], at which the slope of the cumulative curve remains relatively constant, with a slight decrease, mainly due to the congestion near the exit.
- (4) *Saturation*. This stage is usually characterized by the uneven use of the exits as the number of passengers in the coach decreases. The flow rates of some doors drop to zero in advance, which leads to a cliff-like fall of the slope of the cumulative curve, that is, the so-called "saturation." This stage will disappear in evacuations with all the exits evenly used (i.e., run 1 of scenario 9). However, Gu et al. [77] ascribed the saturation stage to the low departing rate of the exit.

As demonstrated in Figure A1 (in Appendix A), the evacuation behaviour of passengers exactly conforms to the proposed four-stage pattern in the experiments with three or two doors opened, except for the aforementioned experiment runs. Based on the above analyses, the nonlinearity of the cumulative curves should be

ascribed to the existence of the acceleration and saturation stages, and thus this characteristic cannot be observed in run 1 of scenario 9.

As presented in Figure. 6e–j, a three-stage pattern excluding the saturation stage, i.e., *reaction*, *acceleration* and *fluctuation* stages, can depict the evacuation process of the experiments with a single exit available in some cases (i.e., scenarios 6 and 11). And, as aforementioned, the acceleration stage may also not exist, leading to a two-stage pattern (i.e., reaction and fluctuation stages) in other cases (i.e., scenarios 2, 3, 7 and 8).

To quantitatively demonstrate the nonlinearity of the cumulative curves in the multi-exit evacuations, the results of the curve fitting for these five cumulative curves are shown in Table 3. As all the fitting models are statistically significant ( $P$  value < 0.001), the adjusted R square values are compared to identify the model with the best fitting performance. It is found that the quadratic and cubic models both fit significantly better than the linear model for the cumulative curves of scenarios 1 and 4, whereas the linear model achieves almost the same adjusted R square value as the quadratic and cubic models in fitting the cumulative curves of scenarios 6, 11 and 8 (as in bold in Table 3). These results indicate the nonlinearity and the linearity of the cumulative curves in the multi-exit and single-exit high-deck coach evacuations respectively and thus demonstrate the proposed multi-stage pattern. In addition, as indicated in Figure. A, the evacuation time distribution exhibits an obvious bell-shaped in the multi-exit evacuations, which also demonstrates the nonlinearity of the cumulative curves. And, a long plateau stage is observed for the evacuation time distribution in the single-exit evacuations, leading to a trapezoid-shaped, which can also reflect the linearity of the cumulative curves.

It is worth noting that although these two theories (the multi-stage pattern in this paper and that in Yang et al. [76] and Gu et al. [77]) seem to have a similar

**Table 3**  
**The Results (Adj. R<sup>2</sup>) of the Curve Fitting**

Types of fitting curves	Multi-exit scenarios		Single-exit scenarios		
	Scenario 4 (Run 2)	Scenario 1 (Run 3)	Scenario 6 (Run 2)	Scenario 11 (Run 1)	Scenario 8 (Run 2)
Linear	<b>.990</b>	<b>.991</b>	<b>.999</b>	<b>.999</b>	<b>.998</b>
Logarithmic	.959	.990	.898	.935	.903
Inverse	.786	.930	.585	.744	.565
Quadratic	<b>.995</b>	<b>.998</b>	<b>.999</b>	<b>1.000</b>	<b>.998</b>
Cubic	<b>.996</b>	<b>.998</b>	<b>.999</b>	<b>1.000</b>	<b>1.000</b>
Compound	.789	.784	.832	.836	.801
Power	.945	.894	.986	.966	.981
S	.994	.971	.919	.989	.913
Growth	.789	.784	.832	.836	.801
Exponential	.789	.784	.832	.836	.801
Logistic	.789	.784	.832	.836	.801

structure to some extent, they depict two kinds of totally different behaviours. The multi-stage theory in Yang et al., [76] and Gu et al. [77]) was established for describing the crowd behaviour in real-life evacuations from buildings during earthquakes. However, the proposed multi-stage pattern in this paper focuses on the evacuation behaviour of passengers in a high-deck coach under normal (experimental) conditions. Thus, the simulation models that intend to recreate the experimental scenarios presented in this paper should also reproduce the observed multi-stage pattern.

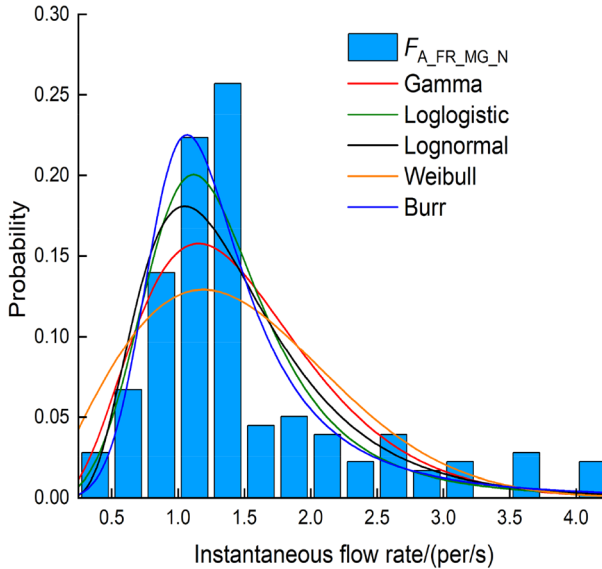
## 7.2. Flow Rate

17 instantaneous flow rate samples from series A and B experiments are shown in Table 4, in which flow samples 4–17 are quoted from Huang et al., [37].  $F_{s,b,p,c}$  denotes the sample of flow rate  $s$ -series (A-series A or B-series B),  $b$ -door (F-front door, R-rear door, E-emergency door, FR-front-and-rear door or FRE-front-rear-and-emergency door),  $p$ -group (MG-mixed age group, ST-young student group or MA-middle-aged group) and  $c$ -condition (D-dim lighting condition or N-normal lighting condition). The Coefficient of Variation demonstrates the considerable fluctuations within each instantaneous flow rate sample [78] and thus justifies the choice of using the probabilistic distribution rather than the constant value to represent the flow rate.

For the sake of simplicity, only the empirical distribution and the estimated five distributions of the first flow sample ( $F_{A\_FR\_MG\_N}$ ) were chosen (as an example) to visualize the fitting goodness of the five candidate distributions, shown in Fig-

**Table 4**  
**The Descriptive Statistics of the Instantaneous Flow Rate Samples**

Order	Flow type	Number	Mean (per/s)	S.D. (per/s)	Coefficient of Variation
1	$F_{A\_FR\_MG\_N}$	179	1.47	0.79	53.7%
2	$F_{A\_F\_MG\_N}$	130	0.96	0.34	35.4%
3	$F_{A\_R\_MG\_N}$	157	0.92	0.26	28.3%
4	$F_{B\_F\_ST\_D}$ [37]	151	0.80	0.19	23.8%
5	$F_{B\_R\_ST\_D}$ [37]	191	0.76	0.20	26.3%
6	$F_{B\_E\_ST\_D}$ [37]	107	0.64	0.16	25.0%
7	$F_{B\_F\_MA\_D}$ [37]	130	0.66	0.20	30.3%
8	$F_{B\_R\_MA\_D}$ [37]	143	0.65	0.18	27.7%
9	$F_{B\_FR\_ST\_D}$ [37]	80	1.26	0.62	51.2%
10	$F_{B\_FRE\_ST\_D}$ [37]	82	1.68	1.09	64.9%
11	$F_{B\_FR\_MA\_D}$ [37]	79	1.01	0.47	46.5%
12	$F_{B\_F\_ST\_N}$ [37]	56	0.91	0.26	28.6%
13	$F_{B\_R\_ST\_N}$ [37]	77	0.81	0.15	18.5%
14	$F_{B\_FR\_ST\_N}$ [37]	104	1.53	0.83	54.2%
15	$F_{B\_F\_MA\_N}$ [37]	60	0.71	0.18	25.3%
16	$F_{B\_R\_MA\_N}$ [37]	73	0.70	0.15	23.9%
17	$F_{B\_FR\_MA\_N}$ [37]	102	1.29	0.72	55.8%

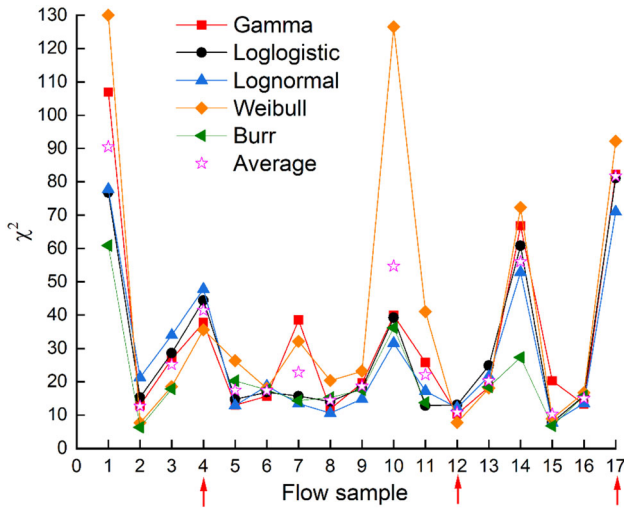


**Figure 7. The empirical and estimated distributions of flow sample  $F_{A\_FR\_MG\_N}$ .**

ure. 7. The estimated parameters and the Chi square values of the five candidate distributions for all flow samples are presented in Table A1 (in Appendix A). The null hypothesis of the Chi-squared test can be expressed as: the estimated distribution is close to the empirical instantaneous flow rate distribution. The results (in Table A) indicate that the selected five candidate distributions can statistically significantly fit 12 out of the 17 flow samples at the significance level of 5%. As presented in Figure. 8, three flow samples, i.e.,  $F_{B\_F\_ST\_D}$  (4),  $F_{B\_F\_ST\_N}$  (12) and  $F_{B\_FR\_MA\_N}$  (17), are not fitted by the Burr distribution. However, for the rest of 14 flow samples, the Burr distribution obtains the first two fitting performance in 10 flow samples and thus has the best overall performance, with the lowest average Chi-square value of 20.6. If taking all flow samples into consideration, the Loglogistic and Lognormal distributions are superior, with comparable average Chi-square values, i.e., 29.43 and 28.18, respectively. Therefore, Burr, Loglogistic and Lognormal distributions are recommended when describing the distribution characteristics of the instantaneous flow rates of passengers evacuating from a high-deck coach.

### 7.3. Alighting Time Gap

The descriptive statistics of 11 alighting time gap samples are shown in Table 5.  $T_{s\_b\_p\_c}$  denotes the sample of alighting time gap  $s$ -series (A-series A or B-series B),  $b$ -door (F-front door, R-rear door or E-emergency door),  $p$ -group (MG-mixed age group, ST-young student group or MA-middle-aged people group) and  $c$ -condition (D-dim lighting condition or N-normal lighting condition). Similarly, Fig. 9



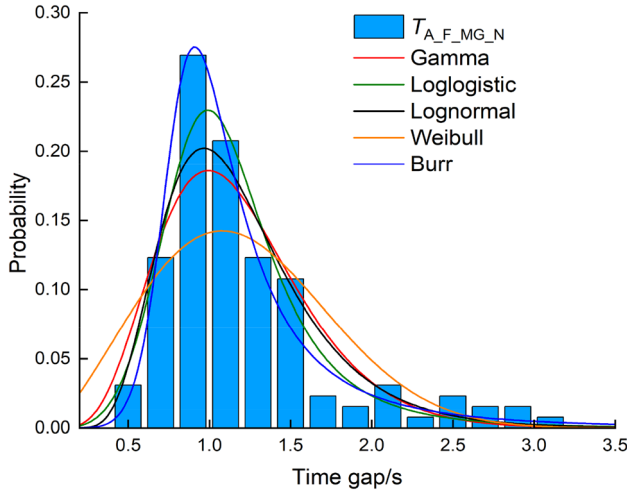
**Figure 8. The Chi-square value of the estimated distributions for all flow samples. The red arrows indicate the flow samples that are not fitted by the Burr distribution.**

presents the empirical distribution and the estimated five distributions of the first alighting time gap sample ( $T_{A\_F\_MG\_N}$ ) (as an example) to show the fitting goodness of the five candidate distributions. The estimated parameters and the Chi square values of all alighting time gap samples are given in Table A2 (in Appendix A). The results show that the five candidate distributions could reasonably account for the distribution characteristics of the alighting time gap samples, in which 9 out of 11 empirical observations are statistically significantly fitted at the significance level of 5%. According to the Chi-square values shown in Fig. 10, it

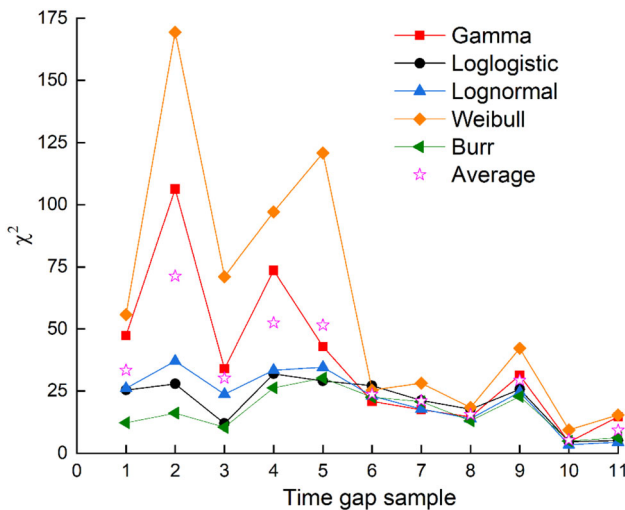
**Table 5  
The Descriptive Statistics of the Alighting Time Gap Samples**

Order	Time gap type	Number	Mean (s)	S.D. (s)	Min	Max
1	$T_{A\_F\_MG\_N}$	130	1.20	0.53	0.52	3.13
2	$T_{A\_R\_MG\_N}$	157	1.21	0.43	0.60	3.03
3	$T_{B\_F\_ST\_D}$	151	1.33	0.37	0.84	2.76
4	$T_{B\_R\_ST\_D}$	191	1.43	0.47	0.72	3.44
5	$T_{B\_E\_ST\_D}$	107	1.68	0.47	1	3.47
6	$T_{B\_F\_MA\_D}$	130	1.63	0.45	0.80	2.92
7	$T_{B\_R\_MA\_D}$	143	1.65	0.47	0.84	3.00
8	$T_{B\_F\_ST\_N}$	56	1.21	0.40	0.72	2.16
9	$T_{B\_R\_ST\_N}$	79	1.27	0.26	0.84	2.04
10	$T_{B\_F\_MA\_N}$	60	1.51	0.40	0.86	2.70
11	$T_{B\_R\_MA\_N}$	75	1.59	0.40	0.92	2.64





**Figure 9. The empirical and estimated distributions of alighting time gap sample  $T_{A,F,M,G,N}$ .**



**Figure 10. The Chi-square value of the estimated distributions for all alighting time gap samples.**

is noticeable that the Burr distribution obtains the best fitting performance, statistically significantly matching the most empirical cases (i.e., 8) and thus achieving the lowest average Chi-square value of 16.86.

Chung et al. [44] suggested using Lognormal and Gamma distributions to describe the alighting time gap distribution of passengers in a high-deck coach evacuation. Our results find that the Burr distribution performs far better than

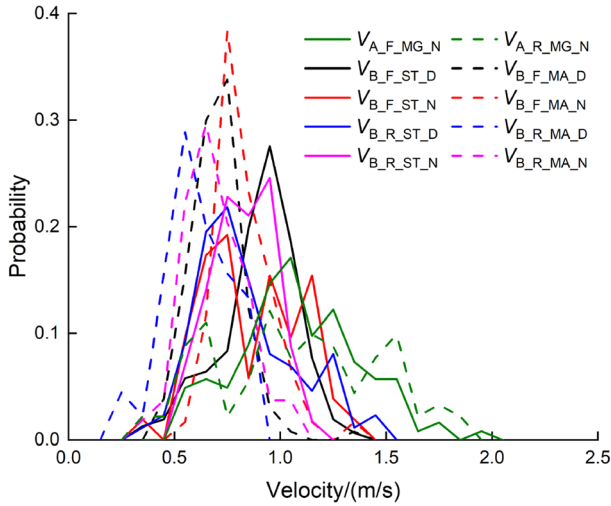
these two suggested distributions. As illustrated in Fig. 9, the estimated Burr distribution is closer to the empirical one, as compared with other estimated distributions. Although the Burr distribution fails to statistically significantly capture the time gap distribution characteristics in the three evacuation conditions (i.e.,  $T_{B\_F\_MA\_D}$ ,  $T_{B\_R\_MA\_D}$  and  $T_{B\_R\_ST\_N}$ ), it still fits them with the proper agreement as compared to other candidate distributions, obtaining the second, the third and the first fitting performance for  $T_{B\_F\_MA\_D}$ ,  $T_{B\_R\_MA\_D}$  and  $T_{B\_R\_ST\_N}$ , respectively.

#### 7.4. Velocity on Stairways

The descriptive statistics and the probability distribution of 10 velocity samples are presented in Table 6 and Figure. 11, respectively. It can be clearly observable that the velocities of passengers generally decrease with the linear density on stairways. As the congestion in front of the stairways obstructs the footage recognition process, only limited velocity data are available in the range of high density. Also,

**Table 6**  
**The Descriptive Statistics of the velocity on Stairways**

Velocity type	Density (per/m)	Number	Mean (m/s)	Min/Max/S.D. (m/s)
$V_{A\_F\_MG\_N}$	0	98	1.12	0.51/1.93/0.31
	0.94	25	0.98	0.56/1.38/0.18
$V_{A\_R\_MG\_N}$	0	59	1.16	0.45/1.86/0.36
	0.84	32	0.93	0.36/1.65/0.38
$V_{B\_F\_ST\_D}$	0	3	1.00	0.90/1.11/0.11
	0.43	80	0.94	0.44/1.31/0.15
	0.87	68	0.87	0.49/1.20/0.18
$V_{B\_F\_MA\_D}$	1.30	5	0.45	0.36/0.53/0.08
	0	3	1.00	0.61/1.31/0.36
	0.43	52	0.71	0.44/1.00/0.11
$V_{B\_F\_ST\_N}$	0.87	75	0.69	0.42/0.93/0.11
	0	1	1.31	–
	0.43	7	0.77	0.58/1.17/0.19
$V_{B\_F\_MA\_N}$	0.87	37	0.92	0.56/1.29/0.19
	1.30	7	0.59	0.33/0.72/0.13
	0	3	0.98	0.93/1.03/0.05
$V_{B\_R\_ST\_D}$	0.43	16	0.85	0.54/1.36/0.20
	0.87	41	0.81	0.65/1.07/0.10
	0	27	0.95	0.58/1.44/0.23
$V_{B\_R\_MA\_D}$	0.725	59	0.79	0.47/1.44/0.21
	0	9	0.63	0.40/0.80/0.15
	0.725	36	0.60	0.27/0.82/0.14
$V_{B\_R\_ST\_N}$	1.449	1	0.39	–
	0	6	0.92	0.78/1.08/0.11
	0.725	51	0.81	0.50/1.19/0.15
$V_{B\_R\_MA\_N}$	0	4	0.64	0.42/0.88/0.23
	0.725	50	0.70	0.38/1.06/0.14



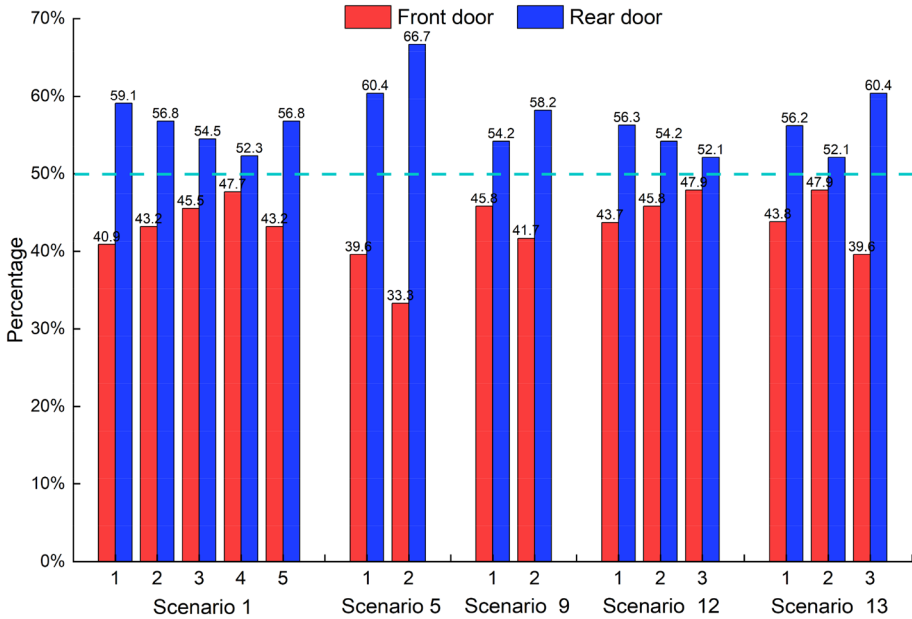
**Figure 11. The probability distribution of velocity on stairways.**

the free velocity data of passengers are scarce as they were involved in crowd movement in the experiments.

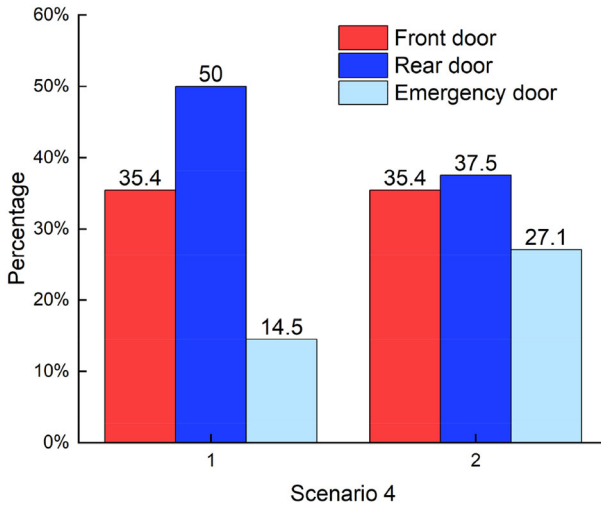
These data provide a reference to set and validate the velocity of passengers on stairways in a high-deck coach simulation model. However, care should be taken when using them as aforementioned.

### 7.5. Exit Choice

The exit choice proportion distribution in the front-and-rear-door evacuations and the three-door evacuations is shown in Figures. 12 and 13. It is found that the passengers exiting through the rear door account for a prevailing proportion (more than 50%) in all the experiments with the front and rear doors available, regardless of the types of high-deck coaches (A/B), age groups (mixed age group/young students/middle-aged people) and lighting conditions (the dim/normal lighting condition). To identify the potential reason behind this phenomenon, the spatial distribution of the exit choice against the seat row number in the front-and-rear-door evacuations is also presented in Figure. 14 where the (final) exit choice of passengers is denoted by a blue triangular shape. It can be clearly observed that the exit choice is closely related to the difference of the seat row numbers between the passenger and the available exits, which reflects the distance between them (as shown in Figure. 3). Generally, the frequency of choosing the front door decreases with the increasing distance between the passenger and the front door. The results in Figure. 14 also indicate that except distance, crowdedness also influences the exit choice of passengers. It was observed that the passengers who were waiting to evacuate through the rear door would change the exit choice when the front door became significantly less crowded than the rear door (shown in Figure. 14, the exit choice of passengers in seat rows 9–12). Most of the passengers



**Figure 12. The exit choice distribution in the front-and-rear-door evacuations.**



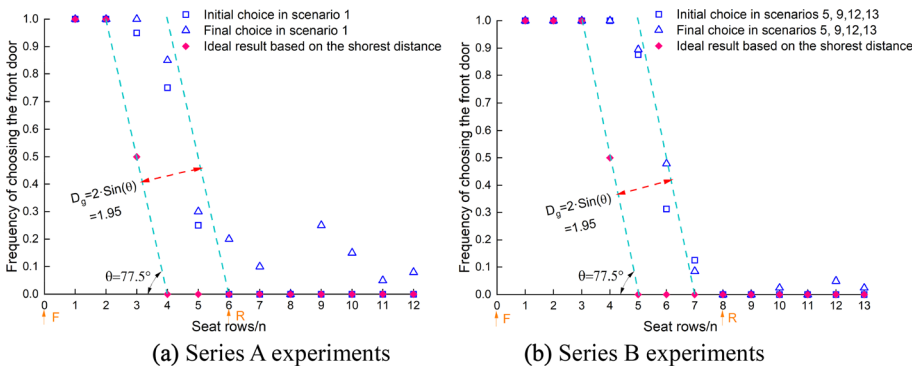
**Figure 13. The exit choice distribution in the three-door evacuations.**

located in the seat rows behind the rear door (i.e., rows 7–12 for high-deck coach A, and rows 9–13 for high-deck coach B) evacuate through the rear door, whereas the exit choice of those passengers located in the seat rows between the front and

rear doors (i.e., rows 1–6 for high-deck coach A, and rows 1–8 for high-deck coach B) depends on the distance to these two exits. Therefore, the observed phenomenon should be ascribed to the design of the longitudinal position of the rear door, which makes more passengers closer to the rear door than to the front door.

It is also found that on average, the difference in the proportions of choosing the front and rear doors is more prominent for young students than middle-aged people (i.e., 63.55% in scenario 5 (young students) vs. 56.2% in scenario 9 (middle-aged people), and 56.2% in scenario 13 (young students) vs. 54.2% in scenario 12 (middle-aged people)). A similar trend is also observed for the dim lighting condition, as compared with the normal lighting condition (i.e., 59.9% in scenarios 5 and 9 (the dim lighting condition) vs. 55.2% in scenarios 12 and 13 (the normal lighting condition)). It is also interesting to find that an extremely high proportion (more than 60%) of young students in the dim lighting condition evacuates through the rear door. These results imply that the exit-choice behaviour of passengers may be related to age groups and lighting conditions. The results in Figure. 13 also indicate that a prevailing proportion of passengers exits the coach by the rear door.

For comparison with the observed exit choice behaviour, the ideal exit choice result based on the shortest distance calculation is also provided in Figure. 14 (in a pink diamond shape). It can be clearly spotted that the frequency of choosing the front door in the experiments shifts towards the larger seat row number (the direction of the rear door) as compared with the ideal results. This could be due to the inertial behaviour of passengers (i.e., tend to keep the original status, in this case, the body posture of facing towards the front door), resulting from the fixed seat direction of facing forward. And, another possible explanation could be



**Figure 14. The spatial distribution of the exit choice against the seat row number. The orange arrows F and R indicate the positions of the front and rear doors, respectively. And, the frequency of '0' and '1' means that all passengers choose the rear door and the front door, respectively.  $D_g$  describes the distance between the two parallel green lines, which reflects the gap between the ideal result and the observed frequency of choosing the front door in each plot.**

that congestion and collision induced by the merging of passengers from the two opposite directions in front of the rear door reduce the desire of passengers located in the seat rows between the front and rear doors to choose it, leading to an increase of the frequency of evacuating through the front door. Moreover, it is interesting to find that the gap between the ideal and observed frequencies of choosing the front door is approximately identical (i.e.,  $D_g = 1.95$  seat rows) in series A and B experiments with different types of high-deck coaches (A/B) and age groups (mixed age group/young students and middle-aged people). This indicates that a quantitatively similar exit choice behaviour is observed in the evacuations, regardless of the types of high-deck coaches and the age composition of passengers. It should be noted that the seat pitch is different for high-deck coaches A and B. Furthermore, the exit-choice changing behaviour is generally infrequent during evacuations, with the maximum frequency of 25.0% and 16.6% observed in series A and B experiments, respectively. This is consistent with the observation of Haghani and Sarvi [26] in other evacuation scenarios. Also, a relatively high frequency of changing the exit-choice is observed in the middle seat rows located between the front and rear doors (as compared with the seat rows located at both ends), which implies that the exit-choice changing behaviour is closely related to the relative distance to the different exits.

It should be noted that though the aforementioned phenomena are observed in laboratory experiments, participants are required to evacuate from the high-deck coach as fast as possible once they perceive that the evacuation is necessary, and no purposeful-play behaviour is found based on rigorous video observations, ascribed to the related penalty measures in addition to the incentive compensation for their attendance. And thus the urgency level in emergency evacuations could be properly simulated, which in turn ensures the representativeness of these exit choice behaviour characteristics. However, the inherent limitations (e.g., the mundane realism) of laboratory experiments may potentially impact passengers' behaviour. Thus, data collected from evacuation drills and real emergency cases are needed to further examine and also extend these findings.

## 8. Discussion

Five performance indicators, along with the context information (including the scenarios, the field layouts, the demographics of the participants and the implementation procedures), are presented in this paper. Based on the proposed data-sets, the generic behavioural characteristics of passengers evacuating from high-deck coaches are systematically analyzed, which can deepen the understanding on this evacuation scenario and also can benchmark the configuration and validation of the high-deck coach evacuation models. Specifically, three behavioural characteristics regardless of the evacuation conditions (high-deck coach A/B, the dim/normal lighting condition, and mixed age group/young students/middle-aged people) are found from the two series of experiments:

- (1) The evacuation behaviour from a high-deck coach follows a modified four-stage pattern (reaction, acceleration, fluctuation and saturation stages) or its variants of two/three stages.
- (2) The instantaneous flow rate can be well modelled by the Burr, Loglogistic and Lognormal distributions, and the alighting time gap can be represented by the Burr distribution.
- (3) More than 50% of passengers choose to evacuate through the rear door in the front-and-rear-door evacuations. For the frequency of choosing the front door, the seat row gap between the ideal result based on the shortest distance calculation and the empirical observation is approximately 1.95. Also, the exit-choice changing behaviour is generally infrequent and it is closely correlated to the relative distance to the different exits.

Furthermore, the data are classified according to the evacuation conditions and structured in the distribution form, which not only can facilitate the use of the data-sets but also enable considering the uncertainties of the performance data in the modelling process. Three examples of the practical applications for the proposed data-sets are discussed briefly here.

First, scenario-specific model validation. Performance data of 13 high-deck coach evacuation scenarios are available for the use of the scenario-specific evacuation model validation. In this case, researchers can choose one of the high-deck coach evacuation scenarios as the basis of the model validation according to their intentions. By setting the initial conditions (including the geometry, the passenger composition, the available exits and the environmental conditions) as in the experiments, the outcomes of the simulation model can be compared against the empirical observations to determine its capability.

Second, situation-specific model validation. Since two distinct types of evacuation situations (i.e., the free or hindered flow situations) were included in the data-sets, these combined data-sets are available for the model validation considering specific evacuation situations. For the free or hindered flow situations, the initial conditions and the results in different evacuation scenarios can be combined as a basis to validate the specialized models developed for high-deck coaches under these specific evacuation situations.

Third, applications in safety design, risk assessment and evacuation management. In terms of engineering applications, the evacuation performance data-sets can not only provide a reference for the design (guidelines) of new high-deck coaches and the development of safety regulations, but also assist the risk assessment, planning and management of evacuation activities related to high-deck coaches. For instance, the alighting time gap observed in our experiments can be used to calculate the dwelling time of a high-deck coach in the crowd evacuation planning and management using high-deck coaches [79], which will improve the reliability and practicality of the evacuation plans.

It is universally accepted that the evacuation process involves the decisions at three behavioural levels, i.e., strategic level, tactical level and operational level [32, 80, 81]. Due to the complicated strategic activities, it is difficult to precisely model various behaviours at this level, and thus the duration of the delay (i.e., pre-evac-

uation time) is employed to reflect the effect of this phase in most studies for simplicity [9, 64, 71, 81]. This way, the strategic decisions are independent of the decisions at the latter two interrelated levels. Then, the pre-evacuation time obtained from empirical observations can be directly used as the input parameter of simulation models [71]. It should be noted that only limited pre-evacuation time samples were collected from our experiments due to the use of controlled experiments, which have been presented in our previous work [37]. With more clarified causation mechanism and evolution pattern that can be mathematically formulated, tactical and operational decisions are the main focus of evacuation modelling, as the case in the specialized models of other transport vehicles (e.g., airEXODUS [54], railEXODUS [15, 21], EvacTrain [63], and SIMPEV [82]). These models are based on network nodes or coarse discretized cells and thus are not likely to be applicable to the high-deck coach evacuation scenario featuring compact and confined space. And, some significant behaviour characteristics that are recently demonstrated were overlooked (e.g., the exit-choice changing behaviour [26]), which additionally upgrades this modelling task. Moreover, as indicated in Huang et al., [83], significant modifications based on empirical observations should be made to improve the capability of the traditional evacuation models (e.g., the social force model) to mimic pedestrians' movement in the narrow seat aisle. In the light of this, the proposed data-sets are critically important for the development, calibration and validation of the models dedicated to high-deck coach evacuations. The development of the specialized evacuation model for high-deck coaches will be the subject of our future research.

Moreover, since more than one run were conducted for certain scenarios (as shown in Table 2), the results from these scenarios (i.e., evacuation time curves and exit choice proportions) have to be first averaged over different runs to make a comparison with the (average) quantity obtained from the simulations. Although multiple data-sets may be needed to fully describe occupants' behaviour variability associated with behavioural uncertainty for an individual scenario [61], its optimal number depends on the pre-defined criteria and the interested scenario. In this context, using the arithmetic mean is treated as an effective method to reduce potential errors, though problems (e.g., the representativeness of the average quantity) might emerge for this operation due to behavioural uncertainty.

## 9. Conclusions and Recommendations

This paper presents the high-deck coach evacuation performance data-sets that include five essential and commonly used performance indicators, collected from two series of controlled experiments constituting 13 evacuation conditions. These data are grouped and structured in the distribution form, based on which critical behavioural insights are revealed to promote the understanding on the evacuation from a high-deck coach.

To the best of our knowledge, it is the first time that high-deck coach evacuation data-sets for modelling and simulation purposes are made available in the field of pedestrian dynamics research. The presented data-sets could not only



enable the model configuration and validation for the scenario-specific, the evacuation-situation-specific or the combination of the two aspects, but also provide reliable data support for the risk assessment, planning or management of evacuation activities related to high-deck coaches. Three behavioural characteristics regardless of the evacuation conditions (the types of high-deck coaches, lighting conditions, and age groups) are found. First, passengers' evacuation behaviour conforms to a multi-stage pattern (a modified four-stage pattern, i.e., reaction, acceleration, fluctuation and saturation stages, or its variants of two/three stages). Second, the distribution characteristics of the instantaneous flow rate can be well captured by the Burr, Loglogistic and Lognormal distribution, and the alighting time gap can be well described by the Burr distribution. It is thus suggested that priority should be given to the distribution(s) with the demonstrated superiority in this paper when an appropriate distribution is needed for modelling these two performance indicators. Third, a dominant proportion (more than 50%) of passengers is observed to evacuate through the rear door in the front-and-rear-door evacuations. The empirically observed frequency of choosing the front door shifts towards the direction of the rear door with a magnitude of approximately 1.95 seat rows, as compared with the ideal results (based on the shortest distance calculation). And, the exit-choice changing behaviour is generally infrequent, and it is influenced by the relative distance to the different exits.

It should be noted that the presented data-sets and behavioural insights are obtained from two types of high-deck coaches complied with Chinese design and safety regulations. Significant differences might exist in regulations, guidelines and standards specialized for the design of high-deck coaches in different countries, resulting in different structure characteristics such as the exit configuration. Thus, appropriate consideration should be given when generalizing and transferring our data-sets and findings. In addition, further efforts are needed to expand the data-sets to cover more evacuation conditions (e.g., including various age groups [34], such as school children) and also study the evacuation behavioural difference between them.

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## **Author contributions**

The authors confirm contributions to the paper as follows: study conception and design: RH, XZ and QY data collection: RH, XZ; analysis and interpretation of

results: RH, YY and WD; comment to draft and revised manuscript: YY and WD. All authors reviewed the results and approved the final version of the manuscript.

## **Data Availability**

Data related to series A experiments are recorded in the spreadsheet (titled as 'S1') and available online.

## **Declarations**

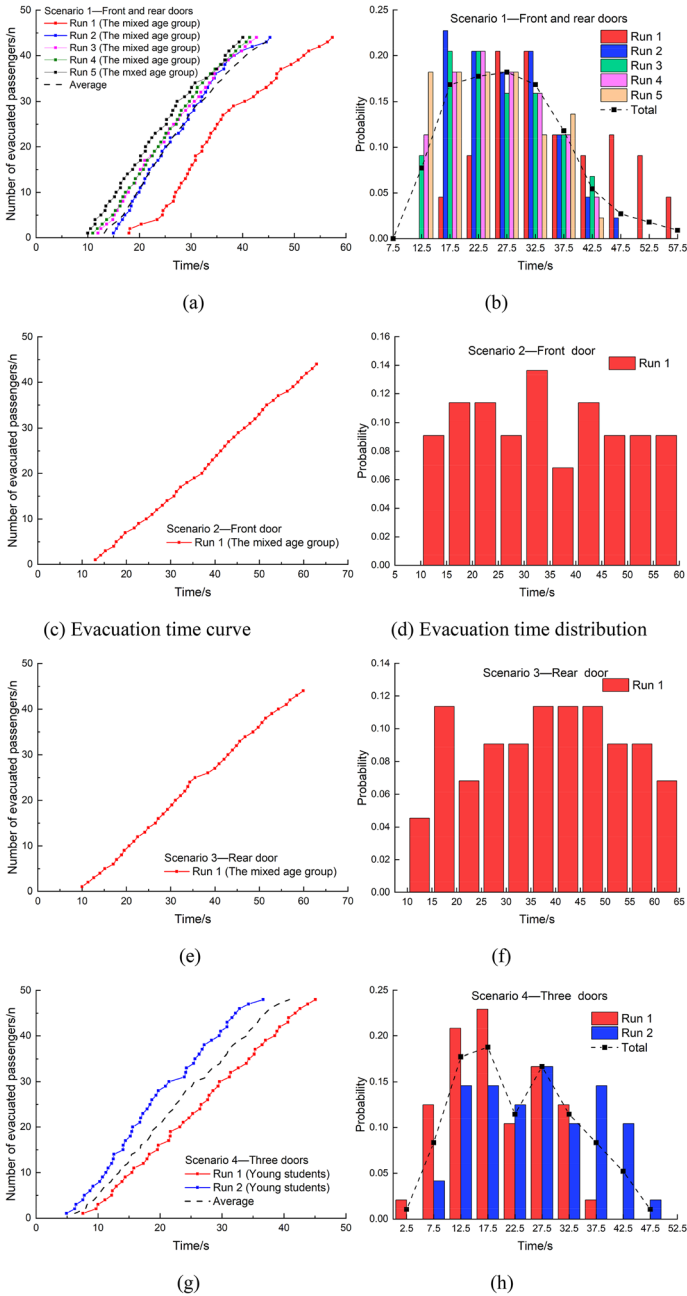
**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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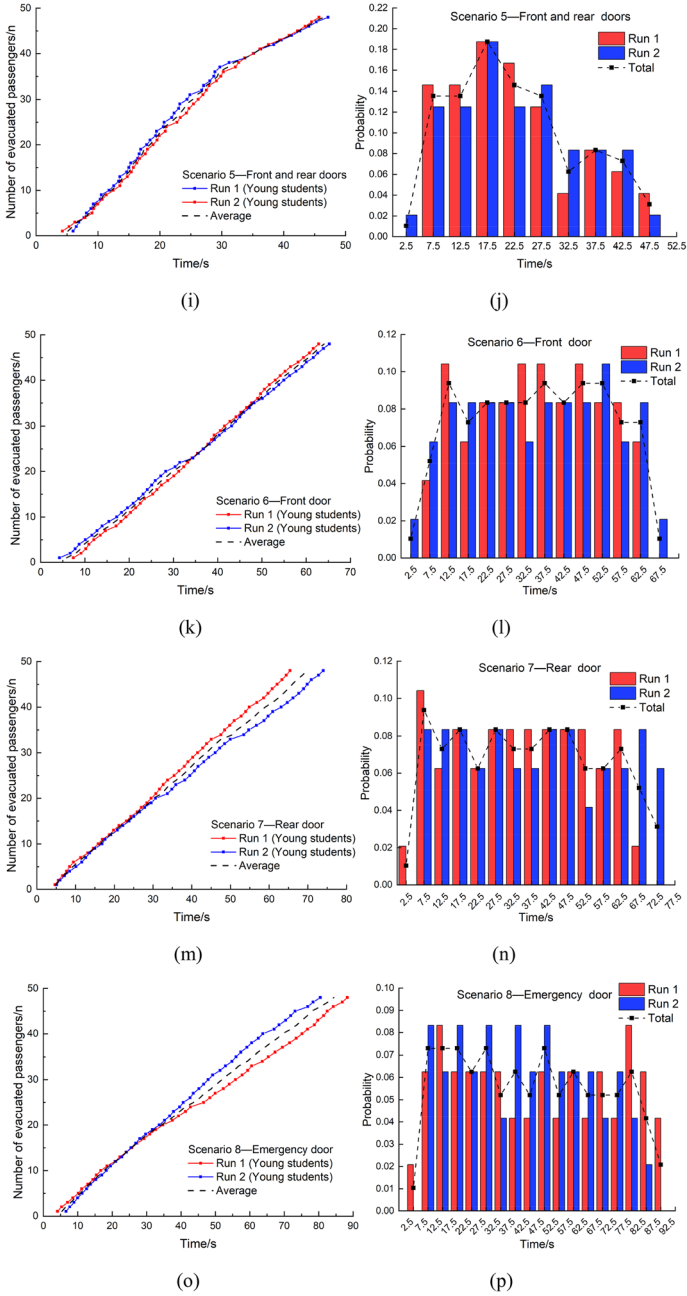
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## **Appendix A**

As shown in Figure. 15. it is clearly observable that the evacuation time curves of the experiments in the same scenario show a consistent trend except for the experiments of scenarios 1, 4 and 9, as described in Figure. 15a, g and q. As run 1 of scenario 1 (i.e., Figure. 15a) is the first experiment run conducted (for series A experiments), passengers were observed to spend much longer time learning how to operate the emergency device of the available doors, and the rear door was still unopened when some passengers have exited from the front door, resulting in a significant delay of the overall evacuation. In run 1 of scenario 4, only 7 passengers exited the coach through the emergency door, and this number was nearly double in run 2 (i.e., 13 passengers). Also, the longer pre-evacuation time is observed. Thus the evacuation was prolonged in run 1, as indicated in Figure. 15g. As for scenario 9 (i.e., Figure. 15q), the middle-aged passengers took considerable more time to initiate the evacuation in run 1, as compared to run 2. It



**Figure 15. Evacuation time curves (the plots on the left) and histogram distributions (the plots on the right) associated with series A and B experiments.**



**Figure 15. continued.**

should be noted that the first experiment run of scenarios 1, 4, and 9 is also respectively the first experiment in which the three age groups of passengers participated. Though these observations indicate the presence of the learning behaviour in our experiments, it mainly makes passengers' evacuation performance at the strategic level between the first and the second experiment runs different. This impacts the total time to evacuate, but not the dynamics of the evacuation. As for the tactical decisions, the learning behaviour is only observed to increase the use of the emergency door in scenario 4, and no prominent effect is found in the

**Table 7**  
**The Estimated Parameters of the Five Candidate Distributions for the Flow Samples**

Flow type	Estimated distribution	a	b	c	$\chi^2$ (the critical value of the $\chi^2$ test)
$F_{A\_FR\_MG\_N}$	Gamma	4.50	0.33	–	106.96(25.00)
	Loglogistic	0.25	0.26	–	76.86
	Lognormal	0.27	0.47	–	77.72
	Weibull	1.67	2.02	–	130.07
	Burr	1.06	4.97	0.57	60.93
$F_{A\_F\_MG\_N}$	Gamma	7.63	0.13	–	12.90*(15.51)
	Loglogistic	–0.08	0.21	–	15.32*
	Lognormal	–0.11	0.38	–	21.35
	Weibull	1.08	3.12	–	7.64*
	Burr	1.68	3.49	5.45	6.29*
$F_{A\_R\_MG\_N}$	Gamma	11.13	0.08	–	26.87(22.36)
	Loglogistic	–0.12	0.18	–	28.64
	Lognormal	–0.14	0.31	–	34.08
	Weibull	1.00	3.85	–	18.58*
	Burr	1.73	4.09	9.91	17.87*
$F_{B\_F\_ST\_D}$	Gamma	16.70	0.05	–	37.80(26.30)
	Loglogistic	–0.23	0.14	–	44.38
	Lognormal	–0.25	0.25	–	47.82
	Weibull	0.88	3.85	–	35.64
	Burr	–	–	–	–
$F_{B\_R\_ST\_D}$	Gamma	13.15	0.06	–	13.00*(33.92)
	Loglogistic	–0.29	0.16	–	14.75*
	Lognormal	–0.29	0.28	–	12.83*
	Weibull	0.85	3.88	–	26.34*
	Burr	0.90	5.20	2.03	20.32*
$F_{B\_E\_ST\_D}$	Gamma	16.10	0.04	–	15.64*(23.69)
	Loglogistic	–0.48	0.15	–	16.84*
	Lognormal	–0.49	0.25	–	18.72*
	Weibull	0.70	4.34	–	18.01*
	Burr	0.70	5.88	1.69	17.58*
$F_{B\_F\_MA\_D}$	Gamma	12.23	0.05	–	38.51(16.92)
	Loglogistic	–0.46	0.17	–	15.72*
	Lognormal	–0.45	0.29	–	13.48*
	Weibull	0.74	3.51	–	32.19
	Burr	0.52	8.99	0.43	14.32*

**Table 7**  
**continued**

Flow type	Estimated distribution	a	b	c	$\chi^2$ (the critical value of the $\chi^2$ test)
$F_{B\_R\_MA\_D}$	Gamma	13.07	0.05	–	11.81*(30.14)
	Loglogistic	–0.46	0.17	–	14.04*
	Lognormal	–0.46	0.28	–	10.57*
	Weibull	0.72	3.82	–	20.39*
	Burr	0.738	5.16	1.77	15.25*
$F_{B\_FR\_ST\_D}$	Gamma	4.60	0.27	–	19.63*(22.36)
	Loglogistic	0.10	0.28	–	18.17*
	Lognormal	0.12	0.48	–	14.82*
	Weibull	1.43	2.19	–	23.16
	Burr	0.91	4.45	0.62	17.59*
$F_{B\_FRE\_ST\_D}$	Gamma	2.79	0.60	–	39.90(16.92)
	Loglogistic	0.31	0.36	–	39.25
	Lognormal	0.33	0.62	–	31.65
	Weibull	1.68	1.90	–	126.51
	Burr	0.84	4.66	0.36	36.24
$F_{B\_FR\_MA\_D}$	Gamma	6.03	0.17	–	25.79(22.36)
	Loglogistic	–0.06	0.23	–	12.85*
	Lognormal	–0.06	0.4	–	17.17*
	Weibull	1.15	2.35	–	41.02
	Burr	0.93	4.40	0.99	13.76*
$F_{B\_F\_ST\_N}$	Gamma	11.50	0.08	–	10.29*(18.31)
	Loglogistic	–0.11	0.18	–	13.01*
	Lognormal	–0.14	0.31	–	12.18*
	Weibull	1.00	4.05	–	7.73*
	Burr	–	–	–	–
$F_{B\_R\_ST\_N}$	Gamma	27.62	0.03	–	18.47*(23.69)
	Loglogistic	–0.22	0.11	–	24.88
	Lognormal	–0.22	0.19	–	21.59*
	Weibull	0.88	5.92	–	18.10*
	Burr	1.17	6.41	6.92	18.45*
$F_{B\_FR\_ST\_N}$	Gamma	4.46	0.34	–	66.81(22.36)
	Loglogistic	0.26	0.26	–	60.85
	Lognormal	0.31	0.46	–	52.85
	Weibull	1.74	2.00	–	72.32
	Burr	0.79	22.89	0.08	27.32
$F_{B\_F\_MA\_N}$	Gamma	15.93	0.04	–	20.29*(26.30)
	Loglogistic	–0.37	0.15	–	7.80*
	Lognormal	–0.38	0.25	–	7.66*
	Weibull	0.77	4.29	–	8.87*
	Burr	0.820	5.61	2.07	6.73*
$F_{B\_R\_MA\_N}$	Gamma	16.82	0.04	–	13.23*(23.69)
	Loglogistic	–0.44	0.15	–	15.82*
	Lognormal	–0.44	0.25	–	13.53*
	Weibull	0.73	4.35	–	16.70*
	Burr	0.710	6.09	1.48	15.75*
$F_{B\_FR\_MA\_N}$	Gamma	4.20	0.31	–	82.21(25.00)
	Loglogistic	0.07	0.27	–	81.13
	Lognormal	0.13	0.47	–	71.08
	Weibull	1.47	1.95	–	92.18
	Burr	–	–	–	–

**Table 8**  
**Estimated Parameters of the Five Candidate Distributions for the**  
**Alighting Time Gap Samples**

Time gap type	Estimated distribution	a	b	c	$\chi^2$ (the critical value of the $\chi^2$ test)
$T_{A\_F\_MG\_N}$	Gamma	6.52	0.18	–	47.40(22.36)
	Loglogistic	0.08	0.21	–	25.39
	Lognormal	0.11	0.38	–	26.12
	Weibull	1.36	2.37	–	55.78
	Burr	0.85	7.53	0.39	12.22*
$T_{A\_R\_MG\_N}$	Gamma	9.72	0.12	–	106.27(22.36)
	Loglogistic	0.12	0.18	–	27.90
	Lognormal	0.14	0.31	–	37.03
	Weibull	1.36	2.86	–	169.35
	Burr	0.91	9.25	0.38	16.10*
$T_{B\_F\_ST\_D}$	Gamma	14.83	0.09	–	33.97(16.92)
	Loglogistic	0.23	0.15	–	11.91*
	Lognormal	0.25	0.25	–	23.72
	Weibull	1.47	3.50	–	71.10
	Burr	1.06	11.75	0.37	10.41*
$T_{B\_R\_ST\_D}$	Gamma	12.04	0.11	–	73.63(35.17)
	Loglogistic	0.29	0.16	–	31.96*
	Lognormal	0.30	0.28	–	33.43*
	Weibull	1.56	3.39	–	97.07
	Burr	1.21	7.56	0.64	26.28*
$T_{B\_E\_ST\_D}$	Gamma	14.34	0.12	–	42.91(38.89)
	Loglogistic	0.48	0.15	–	29.05*
	Lognormal	0.49	0.26	–	34.62*
	Weibull	1.86	3.57	–	120.82
	Burr	1.59	7.06	0.93	30.26*
$T_{B\_F\_MA\_D}$	Gamma	12.89	0.13	–	20.80(19.68)
	Loglogistic	0.46	0.17	–	27.14
	Lognormal	0.45	0.29	–	23.00
	Weibull	1.80	3.97	–	25.35
	Burr	2.47	4.49	4.88	22.47
$T_{B\_R\_MA\_D}$	Gamma	13.00	0.13	–	17.41*(19.68)
	Loglogistic	0.46	0.17	–	21.19
	Lognormal	0.46	0.28	–	17.76*
	Weibull	1.83	3.76	–	28.19
	Burr	1.76	5.39	1.46	20.71
$T_{B\_F\_ST\_N}$	Gamma	10.35	0.12	–	14.62*(25.0)
	Loglogistic	0.11	0.18	–	17.65*
	Lognormal	0.14	0.31	–	13.86*
	Weibull	1.35	3.16	–	18.37*
	Burr	0.86	12.24	0.25	12.98*
$T_{B\_R\_ST\_N}$	Gamma	26.46	0.05	–	31.30(21.03)
	Loglogistic	0.22	0.11	–	25.72
	Lognormal	0.22	0.19	–	24.63
	Weibull	1.38	5.01	–	42.18
	Burr	1.17	10.18	0.71	22.76

**Table 8**  
**continued**

Time gap type	Estimated distribution	a	b	c	$\chi^2$ (the critical value of the $\chi^2$ test)
$T_{B\_F\_MA\_N}$	Gamma	15.39	0.10	–	4.55*(16.92)
	Loglogistic	0.37	0.15	–	4.67*
	Lognormal	0.38	0.26	–	3.54*
	Weibull	1.67	3.91	–	9.34*
	Burr	1.38	7.46	0.79	4.96*
$T_{B\_R\_MA\_N}$	Gamma	16.80	0.09	–	14.63*(16.92)
	Loglogistic	0.44	0.15	–	5.13*
	Lognormal	0.44	0.25	–	4.52*
	Weibull	1.75	4.29	–	15.37*
	Burr	1.76	5.94	1.69	6.31*

NB: in Tables 7 and 8, the asterisk sign (\*) indicates that the estimated distribution is statistically significantly close to the empirical distribution at the significance level of 5%

front-and-rear-door evacuations, as indicated in Sect. 5.5. This is because passengers normally use the front and rear doors to get on/off the coach and thus are familiar with them. Also, its effect on the operational decisions may be rather limited, demonstrated by a consistent trend of the increase of the evacuation time curves in the same scenario except for the aforementioned cases. Thus the learning behaviour has little effect on our results and the proposed data-sets.

The results imply that manually operating the emergency device to open the door, the underused available exits and the delayed initiation of evacuations may significantly reduce the evacuation efficiency. Then, the third parties who intend to use the data-sets should take these behaviours and the caused results into account. In addition, it is also suggested that regular training and knowledge education may be effective measures to alleviate these problems that emerged in our experiments.

See Figure. 15 and Tables 7 and 8

## SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at <https://doi.org/10.1007/s10694-022-01253-y>.

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