Investigation of bus evacuation flow rates for tunnel fire quantitative risk assessment

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ABSTRACT

To increase the knowledge of bus evacuation in tunnel fire scenarios, we investigated the bus evacuation flow rate in the event of a tunnel fire, starting with a video analysis of the 2012 Hsuehshan tunnel fire in Taiwan, to gain a preliminary understanding of an actual bus evacuation flow rate. Two evacuation situations were manifested with different flow rates: the first one in which bus passengers non-urgently evacuated as in the case of a daily bus experience (the first seven evacuees, 0.28 PPS (Person Per Second)) and another situation in which passengers feel the urgency to evacuate (the next twelve evacuees, 0.67 PPS). Based on the investigation of the real fire incident, we conducted a bus evacuation experiment and a bus alighting observation. And the results of flow rates of normal exit were within 0.69–0.88 and 0.21–0.48 PPS, respectively. These results were similar to the actual flow rates in the two assumed evacuation situations in the Hsuehshan tunnel fire incident (nonurgent and urgent), respectively. Our approach can provide a viable approach to describe evacuation flow rates during tunnel fires. Moreover, using the flow rate of the normal alighting situation was preferable for highly reliable tunnel fire safety evaluation.

1. Introduction

The number of road tunnels is continuously increasing with the rapid expansion of road transportation networks, requiring immediate precautions against emergency situations to ensure road safety. For example, a fire incident in critical infrastructure can be catastrophic (Li and Ingason 2018). In case of a fire, long and enclosed tunnel spaces can make evacuation, rescue, and firefighting extremely challenging. Records of fire incidents in tunnels have led to catastrophic consequences such as the 1999 Mont Blanc tunnel fire incident in France and Italy with 39 fatalities (Duffé and Marec 1999; Beard et al. 2005), the 1999 Tauern tunnel fire incident in Austria with 12 fatalities (Pucher and Pucher 1999; Leitner 2001), the 2001 St. Gotthard tunnel fire incident in Switzerland with 11 fatalities (Turner 2001), and the 2012 Hsuehshan tunnel in Taiwan with 2 fatalities (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). Those incidents showed the importance of preventing tunnel fire disasters, requiring accurate strategies for reducing the risk and consequences of fires. An important aspect of the investigation of strategies to prevent disastrous tunnel fires is the risk assessment, especially for preventing possible casualties during tunnel fires.

Regarding the assessment of tunnel safety against fires, Mikame et al. (2014) investigated the number of people who suffered from smoke in a relatively short road tunnel. The assessment was based on a simulated situation in which a bus carried 50 passengers 125 and 230 m downstream and 30 and 125 m upstream from the fire point at a flow rate of 0.5 people/s (Person Per Second, PPS). The results of the simulation confirmed that, compared to a no bus case, buses with over 40 persons were challenging to evacuate when located 125 m downstream of (far from) the fire source given a wind velocity of 1.2 m/s. Moreover, the flow rate from the bus significantly affects the time for evacuation, which is longer for buses than for passenger cars. In general, fire incidents start with a stratified smoke propagating along the ceiling, which eventually fills the long, narrow, and enclosed tunnel, passengers have to evacuate immediately, regardless of whether or not the vehicle is on fire. A typical scenario describing tunnel fire accident recognition by bus passengers is depicted in Figure 1. On the point-of-view of the bus

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passengers, once bus occurring fire, evacuation is an imminent, immediate, and natural response regardless of the structure of the tunnel (Figure 1 (i)). In the case of a tunnel fire rather than a bus fire, smoke, instead of the fire, becomes a risk factor. Danger warning can be relayed through various means, such as through the driver's instruction, an emergency announcement, and people evacuating to prompt the judgment of evacuation necessity (Figure 1 (ii)). Yamazaki, Yokota, and Kawabata (2015) reported that the bus fire incidents in the tunnel were approximately 2.5% of tunnel fire incidents in Japan. It relatively reflected that the bus passengers in the tunnel mainly faced other vehicle fires (97.5%) but not the bus itself. Mixing the buses, the number of evacuation people increases. In addition, those who evacuate get off the bus and then evacuate, and bus passengers inevitably delay evacuation. Therefore, to reach a reliable risk assessment in tunnel fires, it is necessary to consider the evacuation flow rates as well as the bus fire itself.

Accordingly, we reviewed research on experimental techniques to study the flow rates or egress time in case of evacuees by bus. The participants, bus types, conditions, and purposes of these experiments are presented in Table 1. These studies consisted of assumed fire scenarios (ECE 2006), assumed crash incident, bus incapacitated on land, submergence in water (Sliepecevich et al. 1972; Purswell, Dorris, and Stephens 1970, 1978), specific emergency situations (Shiosaka and Kuboike 1996; Pollard and Markos 2009; Liang, Zhang, and Huang 2018), evacuation training (Abulhassan et al. 2016), and rolled-over orientation incidents (Abulhassan et al. 2018). Nonetheless, the focus seemed to be incident scenarios related to the bus itself, signifying that a study on bus evacuation during the fire at a location distant from the bus has not been emphasized or clarified yet. From the above, an important factor for tunnel fire safety evaluation is how the passengers get off the bus.

Hence, the objective of the present study was to clarify evacuation flow rates from buses in tunnel fire incidents for highly reliable risk analysis. As the first step, we aimed to study the exit flow rate of bus evacuees. The paper is structured as follows: Section 2 presents an investigation of the flow rate and behavior of the evacuees during the actual bus evacuation during the 2012 Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). Based on the results, Sections 3 and 4 provide experimental and observational assessments of the bus exit flow rate. A comparison of real scenarios and the results of the present study are discussed in Section 5. Since we focus on evacuation from buses in the present paper, we describe evacuation except for general getting off.

2. Bus evacuation during the Hsuehshan tunnel fire incident

2.1. Incident description

The Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) occurred on 7 May 2012, 10.8 km from the Taipei side exit of Taiwan, leaving 36 casualties. The tunnel is 12.9-km long, has a longitudinal inclination of 1.26% and emergency exits placed at 350-m intervals. The actual incident site is shown in Figure 2. Two buses were involved in the incident in the tunnel: one was eventually caught by fire (Bus 1 in Figure 2), while the other was not (Bus 2 in Figure 2). The fire was due to Bus 1 hitting a small vehicle before hitting Bus 2, resulting in the fire that initiated at Bus 1 at approximately 1:24 PM. Within 30 s of the collision, the people in Bus 1 began evacuating. Bus 1 had two doors, the front, and emergency exits. All evacuees, including the driver, exited the bus from the emergency exit because the collision occurred at the front of the bus (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017; Liberty time net 2012). Fortunately, no casualty on the bus was recorded. The ensuing fire was rated at 25–30 MW and was extinguished.

Figure 1. Scenarios of fire incident recognition passengers.
Table 1. Past studies on bus experiments vs. the present study.

| Bus type | School bus | Intercity bus | Tour bus | Intercity bus | School bus | School bus | Fixed-route bus | Tour bus |
|----------|------------|---------------|----------|---------------|------------|------------|----------------|---------|
| Door type | Normal or Emergency | Emergency | Normal | Normal or Emergency | Normal or Emergency | Normal or Emergency | Emergency | Normal or Emergency |
| Scenario | Emergency | Emergency | Emergency | Emergency | Emergency | Emergency | Emergency | Emergency |
| #Participants | 15–60 (half male, half female) | 38 | 45 Total 135 | 24 | 45 (30 males, 15 females) | 54–56 | 52–63 Total of 475 (251 males, 224 females) | 39–46 Total of 126 (66 males, 60 females) | 63–66 |
| Age | 6–12 and 13–56 | Unknown | Unknown | 8–73 | 25–45 | 35–55 | 5–9 | 5–8 | Unknown |
| Purpose | Study on the factor involved in the escape from a crashed vehicle. | Study of various bus survival factors. | Study of worst scenarios for bus evacuation. | Design for the emergency equipment and guide board. | Evaluate the evacuation safety for bus fire. | Identify human factors related to bus emergency egress. | Measure school bus baseline emergency evacuation times. | Assesses the ability of children for operating emergency doors in rolled-over orientations. | Verify simulation results and adjust the parameter of the bus evacuation model. | Clarify bus evacuating flow rates in tunnel fires. |

Pollard and Markos (2009)
Abulhassan et al. (2016)
Shiosaka and Kuboike (1996)
Purswell, Dorris, and Stephens (1972)
Liang, Zhang, and Huang (2018)
ECE (2006)
Sliepcevich et al. (1972)
Purswell, Dorris, and Stephens (1978)
Purswell, Dorris, and Stephens (1970)

Japan: 16 (15 males, 1 female)
Taiwan: 20 (10 males, 10 females)

Japan: 21–63 mean: 25.8
Taiwan: 23–37 mean: 29.0
within 45 min. In particular, the fire in Bus 1 started at the front, and the emergency tunnel exit was located at the rear end of the bus. Bus 1 stopped 25 m from an emergency exit, and Bus 2 stopped 105 m from an emergency exit.

Because the evacuation process of Bus 2 was not recorded by the CCTV in the tunnel, we primarily investigated the evacuation behavior from Bus 1 from the CCTV camera footage, questionnaire records in the review report (Taiwan Area National Freeway Bureau 2013), and the news of this fire incident (Liberty time net 2012). 22 of the 23 evacuees of Bus 1 aged 9–81 years old (1 driver, 21 passengers, and a baby younger than 1 year old), and 21 of the 23 evacuees suffered from injuries (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017).

After the bus collision, the first male evacuee opened the emergency exit to see what happened, and then he carefully evacuated from the bus, followed by second–fourth evacuees and then by fifth–seventh evacuees (including 6th as a baby held by his/her mother (6th), hence we count baby’s time gap elapsed time same as his/her mother). Here, the first evacuee returned to the bus for assistance as the fifth evacuee was evacuating. An analysis of the evacuating time revealed a mean time of 18.1 s from the first to the seventh evacuees. During this time, there was only smoke and a relatively small fire at the front of the bus. These evacuees carefully alighted the bus as they normally would; no urgency was apparent in the video record.

Subsequently, the eighth unconscious female evacuee was assisted by the first evacuee, who seemed to have trouble evacuating as he hugged her, thus requiring approximately 31.2 s to complete the bus exit. During the evacuation of 8th to 19th evacuees, we observed that they urgently evacuated. Moreover, the time gap between the 19th and 20th evacuee was 7.3 s, which was due to the 20th evacuee having been impeded by the 9th evacuee, who had returned to the bus to assist the remaining evacuees. Approximately 43.9 s later, the 21st evacuee slowly evacuated by himself. Finally, the 22nd evacuee, an elderly injured female was assisted by evacuees 5, 9, and 15. The last two evacuees, who were 81 and 77 years old, respectively, had longer evacuating times than the other evacuees did. This may have been because of the age of the 21st evacuee and injury of the 22nd evacuee.

Based on our analysis of the Hsuehshan tunnel fire incident, we considered that the actual bus passenger evacuating was a discontinuous process and that there was a possibility of at least two evacuation situations: nonurgent and urgent evacuation.

Upon checking the CCTV record from the Hsuehshan tunnel fire incident, there was fire and smoke at the front of the bus (close to the driver’s seat), but the wind flowed from the back of the bus to the front; thus, the smoke did not significantly affect passenger evacuation because the smoke did not reach the evacuees. For this reason, we have excluded the influence of smoke and toxic fumes in our analysis of the evacuation flow rate for this study.

### 2.2. Flow rate calculation

We calculated the flow rate of passenger evacuation as a common measure to reflect exit effectiveness during an evacuation in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) to specifically describe the behavior of bus evacuees. Pollard and Markos (2009) calculated the flow rate of bus exits using the formula: flow rate = subject count (person) / (finish time [sec] – start time [sec]), expressed in persons per minute (PPM). Fridolf, Nilsson, and Frantzich (2014) used "the number of persons passing through per unit width per unit time" to describe the exit flow rate of passengers from a vehicle. For building evacuation, Proulx (2002) used an exit flow rate divided by the width of the exits as these are often wide enough to accommodate multiple pedestrian flows. Nevertheless, for buses, the commonly used exits allow only a single person to pass at a given time; hence, we excluded the exit width in the calculation of flow rate during bus evacuation.

For this study, we defined the flow rate as the number of persons that pass through the bus exit per unit time. The cumulative number of alighted passengers was plotted in the y-axis, and the cumulative time gap between the two passengers was plotted in the x-axis for corresponding. And then the flow rate was
evaluated through a linear regression analysis using the method of least squares. Its unit was persons/sec [PPS]. In past studies, Persons Per Minute (PPM) was often used in describing the flow rate of exit. However, to distinguish the difference in flow rate more detail, Persons Per Second (PPS) was used to express the unit of the flow rate in this paper. A person was considered to have evacuated upon stepping out of the bus. We conducted a frame-by-frame analysis of the videos recorded at the exits using a frame interval of 1/60 s or 1/30 s and considered the resolution accuracy to be sufficient in determining the time point when a person had alighted the bus.

Moreover, the passengers’ counts minus one and then dividing by the exit flow rate can further calculate the movement time of passengers evacuating from the bus exit. The equation was as follows.

\[ \text{N-1/ Exit flow rate [PPS]} = \frac{\text{Movement time [s]}}{N} \]

\( N \): number of people.

### 2.3. Actual bus evacuation flow rate

The evacuees’ evacuation could be divided into three main groups, namely, (1) 1st to 7th, (2) 8th to 19th, and (3) 20th to 22nd evacuees. The respective flow rates were determined by the calculation process described in Section 2.2.

Such classification could be explained as follows. Based on the video recording of the 2012 Hsiehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017), the 1st to 7th evacuees of the first group who checked the situation and gradually evacuated, as in the case of normal passengers getting off the bus. Moreover, the first group evacuated with the average time gap of 3.0 s. For the 8th to 19th evacuees, they evacuated with urgency. This group demonstrated evacuating with the average time gap of 1.6 s, significantly faster than the first group. Finally, the evacuation of the last three evacuees was within irregular time gaps of 7.2–43.9 s. We calculated the flow rates of the first and second groups, as well as the total flow rate (considering 23 bus evacuees), as 0.28, 0.67, and 0.17 PPS, respectively. Since 20th, 21st, and 22nd evacuees took significantly long evacuation time, they did not need to be additionally computed by linear regression analysis. It was evident that the part of the above flow rates was slower than that of 0.60 PPS and 1.17 PPS in bus evacuation experiments conducted by Pollard and Markos (2009) and ECE (2006). Therefore, based on characteristics in the evacuation flow rate above, we further assumed that bus evacuation in a tunnel fire should incorporate the following situations:

1. **Nonurgent situation:** Although having perceived danger, passengers were not aware of the emergency. Therefore, passengers carefully and slowly alighted the bus as they normally would, as in the case of the first group.
2. **Urgent situation:** Passengers become increasingly aware of the escalating danger and thus increase their urgency and awareness of the need to evacuate immediately and quickly, i.e., in the case of the second group.
3. **Time delay:** Owing to specific reasons, i.e., injury (8th and 22nd evacuees), old age (21st evacuee), and resistance to evacuate (19th evacuee), 4 persons/23 evacuees (7.4% of the evacuees) demonstrated longer evacuation time than others. In the present study, we consider a time gap of more than 7 s as a criterion which means the time delay.

### 3. Bus evacuation experiment

The bus evacuation flow rate analysis carried out in Section 2 for the Hsiehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) manifested a classification of different evacuation times in different groups, wherein some flow rates were slower than those observed by Pollard and Markos (2009) and ECE (2006). Previous experiments did not reproduce flow rates for bus evacuation in a tunnel fire because exit designs in those experiments were different. Therefore, we conducted a bus evacuation experiment under controlled conditions (i.e., bus types, seat utilization, and participant composition) to serve as a preliminary approach for examining whether bus evacuation flow rate in a tunnel fire is reproducible.

#### 3.1. Bus types and conditions

According to previous studies, the types, location, and numbers of exits are key factors influencing passenger evacuation time (Sliepcevich et al. 1972; Purswell, Dorris, and Stephens 1970, 1978; Pollard and Markos 2009); nonetheless, these studies were not primarily based on the scenario of bus evacuation in tunnel fires. For us to provide a well-represented clarification of the actual evacuation flow rate, we perceived the need for comparing related data. Given the many existing designs and regulations governing bus exits that vary from country to country, we provided a preliminary review of the relevant regulations on the normal and emergency exits in the USA (NHTSA, DOT, § 571.217 2010), Europe (UNECE, Regulation No.107 2015), Japan (MLIT, Safety Standard for Road Transportation Vehicles 2016), and Taiwan (MOTC, Transportation Standard, Road Transportation Safety Standard 2013), as provided in Table 2.

In the USA (NHTSA, DOT, § 571.217 2010), buses designed to carry fewer than 45 passengers are
### Table 2. Bus exit regulations in each country.

| Country | Capacity [number of people] | Number of normal doors | Emergency exit types | Window | Door | Roof |
|---------|-----------------------------|------------------------|----------------------|--------|------|------|
| USA     | 1–45                        | 1                      | No                   | (Necessary) (Either door or roof) |       |      |
|         | 46–62                       | 1                      |                     |       |      |      |
| Europe  | 9–45                        | 2                      | (Necessary) (Either window, door, or roof) |       |      |
|         | (or one normal door and one emergency door exit) |                        |                     |       |      |
|         | 46–70*                      | 2                      | (Necessary) (Either window, door, or roof) |       |      |
| Japan   | 30–                         | 1                      | No                   | Necessary | No |      |
| Taiwan  | 32–                         | 2                      | Necessary            | Necessary | Necessary |

* means the provision for bus type “Class A”: vehicles designed to carry standing passengers; a vehicle of this class has seats and shall have provision for standing passengers.
required to have normal door exit and either an emergency door or a roof exit. In Europe (UNECE, Regulation No.107 2015), such buses are required to have at least two normal door exits (or one normal door and one emergency door exit) and additional emergency exits (door, window or roof exit). In Japan (2016), such buses are required to have normal and emergency door exits. In Taiwan (MOTC, Transportation Standard, Road Transportation Safety Standard 2013), such buses must have a normal door exit, an emergency door exit, emergency window exits, and an emergency roof exit.

Moreover, in the USA (NHTSA, DOT, § 571.217 2010), buses designed to carry 47 passengers or more must have a normal door exit, an emergency door exit (or emergency roof exit), and an emergency window exit. In Europe (UNECE, Regulation No.107 2015), such buses are required to have at least two normal door exits, and additional emergency exits (door, window, or roof exit). In Japan (2016) such buses do not particularly emphasize the relation between the number of emergency exits and the number of passengers. In Taiwan (MOTC, Transportation Standard, Road Transportation Safety Standard 2013), such buses must have two normal door exits, an emergency door exit, emergency window exits, and an emergency roof exit.

Taiwan's bus regulations are similar to those of Europe. Nevertheless, Taiwan still has the strictest regulations, and Japan has relatively flexible regulations. Meanwhile, the incident bus in 2012 Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) was also manufactured in accordance with the Taiwanese regulations. To examine the reliability of the flow rate approach, we chose a bus that abides by Taiwanese regulations (strictest) and another by the Japanese regulations (relatively flexible) for comparison.

We conducted the experiments on sightseeing buses in Japan and Taiwan to measure the evacuation flow rate. The Japanese bus had a capacity of 28 passengers, a normal exit at the front, and an emergency exit in the rear. The emergency exit was 1.4 m high from the ground, as shown in Figure 3 (i) and Table 3. On the other hand, the Taiwanese bus had a capacity of 43 passengers, two normal exits (one at the front and another in the rear), and an additional emergency exit in the rear, as shown in Figure 3 (ii) and Table 3. These aside, the two buses had almost the same seats and normal exits (front and rear).

Participants were recorded by video cameras while exiting the buses. Lights inside the buses were turned off, and daylight was attenuated by curtains closed, except at the front window so that the luminance was still sufficient to identify the configuration on the bus. To ensure the safety of participants, hazardous factors such as fire and smoke were not present. Also, as the focus was on flow rates from the normal or emergency exits, evacuation via windows was not considered.

![Figure 3. Internal structure of the buses used in experiments.](image-url)
Table 3. Experimental bus (comparison between Japanese and Taiwanese buses).

| Type       | Japan | Taiwan |
|------------|-------|--------|
| Inside Exit| ![Japan Inside Exit] | ![Taiwan Inside Exit] |
| Front Exit | ![Japan Front Exit] | ![Taiwan Front Exit] |
| Rear Exit  | None  |        |
| Emergency Exit | ![Japan Emergency Exit] | ![Taiwan Emergency Exit] |

exits were opened before the experiments began for both the Japanese and Taiwanese buses.

3.2. Participants, seat utilization, scenarios, and flow rate computation

The Japan experiment involved 16 participants (15 men whose ages ranged from 21 to 62 years and one 30-year-old woman). Overall, the average age of the participants was 25.8 years. The Taiwan experiment involved 20 participants of an equal number of men (from 23 to 37 years old) and women (23 to 36 years old). Overall, the average age of the participants was 29.0 years.

For both experiments, we investigated the flow rate in which the bus seat utilization rates (person/seats) were correspondingly 57% and 47%. In the Status of the Nation’s Highways, Bridges, and Transit: Conditions & Performance conducted by the U.S. Department of Federal Highway Administration (2015), the average utilization of the seating capacity was reported to range from 28.3% to 49.1%, depending on the modes of bus transit. Meanwhile, a past study on bus alighting observation (Pollard and Markos 2009) revealed passenger flow rates of 0.22, 0.30, and 0.30 PPS under seat utilization rates of around 87%, 70%, and 52% respectively. This result implies that seat utilization is not the main cause of changes in the flow rates. Because seat
utilization rate conditions do not considerably affect the evacuation flow rates and a full bus would be a rare case, the present study chose suitable bus seat utilization rates that would better reflect actual scenarios of bus evacuation in a tunnel fire incident.

The experiments were carried out for nine variants of the same scenario for each exit with only one exception. The assumed scenarios described to the participants included the following: “The bus in which you are traveling encounters a fire in a tunnel and makes an emergency stop. There is a danger of fire in the tunnel. You should decide to evacuate the bus.” and “Please do not think of this as an experiment and respond to the situation.” In Japan, the experiment for the normal situation, i.e., no evacuation, was conducted (J-FN, Japan-Front door, and Normal alighting) once. Eight cases were considered for the emergency: Three cases involved no luggage, the evacuation was done using the front door (J-F1, J-F2, T-F), and some participants provided input on the laid-down-seats case after the experiments and stated they could remove the seatbelt more quickly than in the case of an upright seat position. One case involved all seats laid down, and evacuation was done using the front door (J-FS, Seat laid down). One case involved half of the passengers bringing luggage, which was emulated by two 2-L water bottles in a bag (J-FL, Luggage). One case involved no luggage, and evacuation was done using the rear door (T-R, Rear door). Two cases involved no luggage, and evacuation was done through the emergency doors (J-E, T-E, Emergency exit). Respective conditions for all cases are shown in Table 4.

Flow rate calculation was performed using the same process described in Section 2.2. The unit of flow rate was persons/sec (PPS), and the value of $R^2$, or the fitness between the regression line and the data, was calculated to present variations in the flow rate of persons. Moreover, the frame interval was 1/60 and 1/30 s for the Japan and Taiwan experiments, respectively. In addition, because we started timing once the first passenger touched the ground, whether the door was open or close was irrelevant in the timing process. The survival rate and the total time of evacuation were not included.

### 3.3. Experimental results

The flow rates for Japan and Taiwan are shown in Figure 4. The flow rate for the front exit was between 0.81 ($J$-$F_2$, square of correlation coefficient $R^2 = 0.996$) and 0.88 PPS ($J$-$F_1$ and J-$F_3$, $R^2 = 0.997$). With half of the participants with luggage, the flow rate was 0.85 PPS ($J$-$F_L$, $R^2 = 0.998$). Hence, the flow rate in $J$-$F_L$ was almost the same as those in $J$-$F_1$ and $J$-$F_2$. Additionally, in Figure 4, the experiments were compared to experiments conducted by Pollard and Markos (2009) and ECE (2006) using a tour bus having similar normal and emergency exits as in the present study; flow rates based on the assumption of evacuating in emergency situations were likewise presented. The flow rate for the front door as demonstrated by Pollard and Markos (2009) was 0.60 PPS under the assumption that “passengers were slightly late for work,” and 1.17 PPS as reported by ECE (2006) under the assumption that “there is no severe injury on board, but there is a certain panic.” Moreover, since the rear and the front exit in the present experiment were almost the same, we compared the flow rate of the rear exit to those for the front exits. Specifically, the flow rate measured at the front and rear exits were 0.70 ($J$-$F_N$, $R^2 = 0.999$) and 0.69 PPS (T-$R$, $R^2 = 0.999$), respectively, which were relatively close to those reported by Pollard and Markos (2009) having similar bus exit width (0.61 m) as that in the Taiwan bus experiments.

Figure 5 showed the flow rates for the emergency exits of present experiments, the experiment by ECE (2006) and the Hsu-van tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). Respectively, these were 0.49 ($J$-$E$, $R^2 = 0.975$) and 0.68 PPS (T-$E$, $R^2 = 0.999$) for the experiments conducted for Japan and Taiwan.

Because the bus emergency exit in the Hsu-van tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) was similar to that in the Taiwan experiment, we chose the emergency exit flow rate of the latter for comparison, as shown in Figure 5. The result revealed that the flow rate for the 2nd group (0.67 PPS) was close to that in Taiwan experiments. Nevertheless, the flow rate for the first group (0.28 PPS) was not reproduced well, indicating that the current experiment could merely reproduce part of the bus evacuation flow rate for an actual tunnel fire.

### 3.4. Discussion of experimental results

The result for our experiment was quite lowered than that for the ECE (2006) experiment (see Figures 4 and
One possible explanation could be the influence of the passenger perception on the evacuation. In the ECE (2006) experiments, the situation assumption was “There is no severe injury on board, but there is a certain panic;” in contrast, the situation assumption in the present experiment was “The bus on which you are traveling encounters a fire in a tunnel and makes an emergency stop. There is a danger of fire in the tunnel. You should decide to evacuate the bus.” The perceived levels of emergency for the participants were reasonably different. However, other experimental conditions, e.g., participant composition, physical ability, or exit condition, contributed to the uncertainty between the present and ECE (2006) experiments. The flow rates in ECE (2006) and Pollard and Markos (2009’s) studies were calculated from the ratio of the passenger numbers to the total alighting time, rather than by the least-squares method. Thus, the comparison above should be dealt with caution.

Additionally, the exit design with a low height (as installation position from the ground) difference and step is favorable for bus evacuation. Figure 6 showed the detailed elapsed time of each participant exiting the bus emergency exit in case of Japan experiment (J-E), Taiwan experiment (T-E), and Hsuehshan tunnel fire 2nd group (evacuee 8th to 19th). In the Taiwan
The flow rate was steady at 0.68 PPS. This value is close to the Hsuehshan tunnel fire 2nd group (0.67 PPS). In the Japan experiment (green), the flow rate for the first group (in their 20s) was 0.56 PPS, and that of the final three persons was 0.19 PPS, for a total mean flow rate of 0.49 PPS (red).

Figure 7 shows sequential images of the evacuating behavior of the last three participants (a 27-year-old male, a 30-year-old female, and a 62-year-old male) in the Japan experiment. Here, the time 0 s indicated the time point at which the previous participants have finished passing through the exit, and the red numbers represented the evacuation time. As the emergency exit was 1.4 m from the ground, participants needed to jump down to evacuate the bus. The first 14 participants (including the 27-year-old male) jumped promptly in 1.8 s (the average evacuation time of an adult male), but the final two participants hesitated to evacuate. Before descending, the female sat on the floor for 4.0 s and jumped to the ground in 1.0 s, for a total of a 5.0 s evacuation time. She fell on her knees on her decent. The elderly male descended gingerly, taking 5.6 s to alight the bus and staggered to leave the evacuation location. These two participants moved cautiously and slowly to overcome the height (as installation position from the ground) difference from exit to ground for preventing the possibility of injury. Relatively, in the Taiwan bus, the emergency exit was 0.5 m from the ground, had steps similar to the normal exit, which provided the convenience for passengers evacuating.
4. Alighting observation

To recall, the bus evacuation flow rate of the first evacuee group in the Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) was approximately 0.28 PPS (in Section 2.3), which is much lower than in the current experiment. The experimental approach did not reproduce the evacuation flow rate of the first group. This is likely because passengers do not feel the urgency to evacuate in a real-case tunnel fire; thus, the flow rate can be described as nonurgent alighting. Machek et al. (2007) and Pollard and Markos (2009) conducted bus alighting observations in the visitor center and bus terminal, respectively (see Table 5). Passengers were expected to bring luggage unlike the evacuation situation where bus passengers had no luggage. To examine the conditions in which passengers do not hurry to evacuate during the onset of a tunnel fire, we conducted a bus alighting observation to measure the flow rate.

4.1. Observation site for the assumption of nonurgent evacuation

Observing bus alighting in an actual tunnel is virtually impossible as it is dangerous. Similarly, observing the situation of a bus stopping in the tunnel to let passengers alight is impossible during the standard operation of a tunnel. Thus, we chose a parking lot as for conducting the observation. Moreover, based on the Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) video record analysis in previous sections, all passengers either had nothing or brought small bags as they exited the bus, which necessarily reflects human behavior in an actual evacuation. Therefore, we chose Ken-roku en, a historical park in Kanazawa (Japan), as the observation location, where passengers typically bring only small luggage and stay for a short period for sightseeing. This environment matched the conditions during the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) and thus was a suitable model for the assumed condition where passengers behave calmly and do not feel the urgency to evacuate at the onset of a tunnel fire.

4.2. Flow rate collection in observation

Measurements at Ken-roku en were made using a stopwatch to protect the privacy of the passengers. Here, a passenger was considered to have exited the bus once they stepped out of the bus. We measured 18 cases for sightseeing buses carrying more than 10 passengers. The total number of passengers observed was 522. Since the observation results were obtained at a tourist spot, the age range of the subjects was approximately 2–70 years. Prior approval was obtained before observations started. The cumulative number of alighted passengers was plotted in the y-axis, and the cumulative time gap between the two passengers was plotted in the x-axis for corresponding. Herein, the flow rate was defined as the slope of a linear regression analysis using the method of least squares, which was the same calculation method employed in Section 2.2. Two observers independently measured when each passenger exited the bus and checked if there had been any mistake regarding the time points.

4.3. Observational results

Figure 8 displays the flow rate results of the present observation, the Hsuehshan tunnel fire data (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017), and those of Machek et al. (2007) and Pollard and Markos (2009). For the present observation, the minimum, maximum, and mean flow rate of 18 cases were 0.21 (R² = 0.967), 0.48 (R² = 0.989), and 0.33 PPS, respectively.

| Table 5. Past studies on bus evacuation vs. the present study. |
|-----------------|-----------------|-----------------|
| Machek et al. (2007) | Pollard and Markos (2009) | The present study |
| **Bus type** | Tour bus | Tour bus | Tour bus |
| **Door type** | Normal | Normal | Normal |
| **Exp or Obs** | Observation | Observation | Observation |
| **Place** | Visitor center | Bus terminal | Historical park |
| **#Participants** | #case 34 | #case 13 | #case 18 |
| | 9–55 | 7–50 | 15–50 |
| | (Total 1334) | (Total 361) | (Total 522) |
| **Age** | Unknown | Unknown | Around 2–70 years |
| **Purpose** | Measure the traffic condition for improving vehicular and pedestrian congestion. | Grasp passenger flow rates that involve variability from individuals with impaired mobility, infants, and toddlers. | Clarify the evacuation flow rates in tunnel fires. |
Because the observation by Machek et al. (2007) and Pollard and Markos (2009) could provide a relative comparison for normal alighting conditions, we chose the cases with more than 10 passengers for comparison in Figure 8. Specifically, the flow rates in Machek et al. (2007)’s study were between 0.10 and 0.45 PPS with an average of 0.29 PPS and those in Pollard and Markos (2009)’s study were between 0.20 and 0.48 PPS with an average of 0.31 PPS.

Furthermore, the flow rates for the first bus evacuee group (1st to 7th evacuees) in the Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) shown in Figure 8 are 0.28 PPS. It revealed that the flow rate of the first evacuee group was in the range of the present observational flow rate. Accordingly, the observed mean flow rate (0.33 PPS) for the present observation was close to the flow rate of the first bus evacuee group, thereby reproducing the flow rate in a real tunnel fire incident.

4.4. Discussion of observational results

To discuss the difference of the flow rate, Figure 9 shows the elapsed times for passengers exiting the bus in the cases of present observation (maximum and minimum flow rate) and Hsuehshan tunnel fire 1st group (evacuee 1st to 7th). In the minimum flow rate case, the first 13 passengers continuously alighted, whereas it took 14 s for the 14th passenger and 13 s for the 16th passenger to alight the bus. These alighting times of over 10 s resulted from the last passengers returning to the bus for their luggage, which impeded and prolonged the alighting of other passengers. Obviously, the discontinuous time distribution reduced the flow rate. Relatively, the maximum flow rate was recorded for passengers who continuously alighted. Nonetheless, the mean of these flow rates (0.33 PPS) still close to the Hsuehshan tunnel fire 1st group (0.28 PPS).

The comparison of present observation and Machek et al. (2007) and Pollard and Markos (2009)’s studies
revealed a consistency between the present observation and past studies in Figure 8. However, the flow rates reported by past studies were calculated from the ratio of the passenger numbers to the total alighting time, rather than by the least-squares method. Therefore, the flow rate comparison in Figure 8 needs cautious treatment. Nevertheless, even though there was a certain variance in bus passenger compositions and alighting conditions, the reliability of the results from the current observation was still high.

Notably, some movement patterns leading to irregular time gaps can be found in the present observation, e.g., passengers acting slowly to prevent falling (ensuring that the two feet touched the same step before moving to the next step when alighting bus exits (6.2–13.0 s), passengers using a crutch to alight the exit (13.6–14.9 s), an adult holding a child’s hands and slowly descending the steps while alighting (25.4 s), and an alighted passenger returning to the bus to search for something but impeding another passenger (8.65 s). On the other hand, the time delay was incurred by the last three evacuees in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017), particularly at time gaps of 7.2–43.9 s. Also, the eighth unconscious female evacuee was assisted by the first evacuee, who seemed to have trouble alighting, thus requiring approximately 31.2 s to exit the bus. Although a general evacuation design was developed to aid the vulnerable people for convenient egression, in Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) the elapsed time of the last three evacuees starting to evacuate was almost the same as the time when the 9th evacuee (a driver) returned to the bus. All phenomena discussed above reflect the possibility of irregular time gaps. The irregular time gaps should be considered as time delay, which possibly occur in an actual tunnel fire scenario.

5. Summary and discussion

The present study provides valuable information regarding bus evacuation in the event of a tunnel fire. The actual flow rates of bus evacuation in the tunnel fire (first and second groups and total flow rate) were compared with experimental and observational approaches for validation.

Considering that the normal bus exit design for the Taiwan and Japan experiments were almost identical and the bus emergency exit designs for the Taiwan experiment were similar to those in the Hsuehshan tunnel fire (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017), we have chosen the normal exit (front and rear) data in the Japan and Taiwan experiments, the emergency exit data in the Taiwan experiment, and the front exit data in the normal alighting observation to compare flow rates in similar exit conditions (Figure 10). The flow rate of the second bus evacuate group (0.67 PPS) in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) was close to the range that of the Taiwan experiment result (0.68 PPS), and the flow rate of the first evacuate group (0.28 PPS) was in the range of the observation-based study results (0.21–0.48 PPS). These results show a significant flow rate variance in the bus evacuation in actual tunnel fires.

The interpretation of different flow rates in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) can be attributed to the presence of two different perceptions (nonurgent and urgent). Typically, a bus fire situation is perceived as an emergency situation. Passengers are expected to evacuate immediately. In the case of Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017), even though the bus has caught fire accompanied by a

![Figure 10. Comparison of the present study with the Hsuehshan tunnel fire incident in 2012.](image-url)
dense smoke, the first bus evacuee group still moved normally as in the case of daily bus passengers. The bus passengers were probably aware of but had the difficulty of estimating the gravity of the danger. Hence, in the initial stage of bus evacuation in tunnel fires, passengers did not feel the urgency to evacuate. In this situation, the normal alighting observation could serve as a viable approach for estimating the flow rate. When passengers were aware that the situation had worsened, they recognized the need for quick evacuation. In such a situation, experimental bus evacuation could serve as an available approach for estimating the flow rate. Overall, two responses of passengers (nonurgent and urgent) are typical during bus evacuation in case of a tunnel fire.

Regarding the mechanism of the situation turning from nonurgent to urgent, we considered the following three possible reasons. Firstly, the driver was guiding the passengers while alighting (Liberty time net 2012). Secondly, we speculated that the difficulty of carrying the 8th unconscious evacuee caused the congestion, and the following passengers waited near the emergency door to get ready for alighting. Then, they went out of the bus immediately when the stairs were free after the 8th evacuee was carried away. Finally, before the second bus evacuee group got off the bus, they might have seen the growing smoke and flames in front of the bus, convinced that the situation had worsened.

To further discuss the trigger that caused turning from nonurgent to urgent response, we reviewed past research related to the effects of psychological factors on evacuation. Leach (2004) analyzed the witness testimonies, survivor debriefings, and official inquiry reports from shipwreck and aircraft emergencies to identify possible factors underpinning “freezing” behavior in disaster. The study mentioned that one passenger of the maritime disaster who expresses that during impact, “I didn’t think. Shock is so disorienting it doesn’t allow us to think clearly.” Most victims in this incident showed varying degrees of bewilderment and confusion. However, another witness reported seeing a man standing, composed and assured, trying to calm those who were frightened. He instructed and helped passengers to put lifejacket for survival. It is evident that people are difficult to estimate the situation in the initial stage of the incident, but instruction would help people to conduct the correct act.

Kuligowski and Milleti (2009) investigated the pre-evacuation time of people in the World Trade Center (WTC) fire event. They also discussed the cues that lead to people arouse their awareness of evacuation and proposed that perception of risk was a direct consequence of environmental cues (i.e. witness a fireball exploding outside). Sherman et al. (2011) further used a linear regression model to study the evacuees of the World Trade Center (WTC) fire event. They reported that a higher perceived risk is related to the shorter time of deciding evacuation.

Proulx and Sime (1991) conducted a fire evacuation experiment in an underground station to discuss the influence on users’ evacuation under different staffing provisions and instruction. With clear information and instruction given by Public Address (P.A.) (i.e. To all passengers. There is a suspected fire on the North/ South escalator between the concourse and platform 1 and 2. Passengers on all platforms should board the first available train. Passengers at the concourse level should leave by the nearest exit. Do not use the lift.), evacuees could act very quickly. Of the 22 evacuees interviewed, 18 (82%) heard the alarm and 11 (50%) heard the P.A., 5 of which thinking they should board a train and the rest leave by the nearest exit. For the first time a majority, 13 (59%) thought it was a real emergency. Proulx (2003) also further investigated human behavior in burning buildings and reported that the smell of smoke or the sight of flames are cues that become stronger and more convincing to the occupant that evacuation is necessary.

Haghani, Sarvi, and Shahhoseini (2020) investigated the evacuation behavior of crowds under high and low levels of urgency. The high level of urgency was simulated by a continuous loud siren, and the participants were asked to imagine they were escaping from imminent life-threatening danger. The low level of urgency was simulated by a simple “go” command (no loud siren was played). It was made known to the participants that the competition would be won by the team with the shortest evacuation time. The results suggested that both total and individual evacuation times were significantly shorter when the scenario was treated as high urgency (i.e. when individuals were motivated to escape quickly). This study relatively implies that sound implying the emergency and an individual’s awareness of dangerous situations are the triggers for the change in the level of urgency.

Thus, obtaining more information (i.e. the sight of flames, the smell of smoke, breathing difficulties, feeling the heat, and hearing the alarm or instruction) leads to a higher perception of risk and contribute to responding urgently. In addition, educating bus drivers, passengers, and all tunnel users are critical to enhancing their perception of risk to accurately recognize the danger and make decisions for evacuation in time.

Moreover, the risk assessment of tunnel fires is necessary to consider bus evacuation in a nonurgent situation rather than an urgent situation. The two reasons related to the aspect of probability and consequence as following.
First, there is a nonurgent situation in evacuating the bus on fire in the real tunnel fire incident. Typically, seeing flames and smoke are strong indicators of fire and the need to escape (Kobes et al. 2010). However, even though the bus accident occurred, starting the fire, the first group (see Section 2.3) still moved slowly in the real case of Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). An investigation of the Mont Blanc road tunnel reveals that many drivers continue driving, rather than attempting to evacuate even though they were aware of gradually worsening visibility (Purser 2009). Bus fire incidents in the tunnel were approximately 2.5% of all tunnel fire incidents in Japan (Yamazaki, Yokota, and Kawabata 2015). Most bus passengers in the tunnel mainly faced fire hazards far from the bus (97.5%). It is expected that bus passengers far from the fire source can only receive limited information. The degree of uncertainty about the danger of the situation would affect the passenger’s awareness of the need for evacuation. The evacuees are extensively increased when buses are stopped in the tunnel. It is also concerned that alighting from a bus takes longer time compared to a passenger car because of its lower exit-to-passenger ratio. To reach a reliable risk assessment in tunnel fires, it is necessary to consider the evacuation flow rates as well as the bus fire itself. Therefore, the scenario of bus evacuation in tunnel fires lead to a high possibility of nonurgent response of those involved.

Second, SP Technical Research Institute of Sweden (Hammarström et al. 2008) conducted real-scale bus fire tests and reported that the available time to evacuate from danger is approximately 200–300 s. The ECE (2006) conducted a bus evacuation experiment and reported that the required evacuation times for 46 adults evacuating from a single door exit were approximately 100–120 s. We further compared these two reports with present studies though a comparison between required safe egress time (ASET) (Proulx 2002) to discuss the influence of different situations on the consequence of tunnel safety assessment. The available safe egress time (ASET) can simply be divided as the pre-movement and movement time. Since the pre-evacuation time was not considered in the present experiments and observations, we took the pre-evacuation time of Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) (i.e. passengers began evacuating after 30 s of the collision impact) and the ECE (2006)’s study as the reference. The movement time can be calculated by We consider the present experiment and observation results as the exit flow rates of an urgent situation (0.69–0.88 PPS) and nonurgent situation (0.21–0.48 PPS) to calculate the movement time.

The comparisons in the case of 46 people (the same as the condition in ECE (2006)’s study) are shown in Table 6.

Table 6 indicates that the RSET of the urgent situation (present experiments) is close to ECE (2006)’s study when considering the urgent situation. Compared with the 200 s of ASET in the SP report (Hammarström et al. 2008), the RSET in the case of the nonurgent situation (present observations) would be 44–97 s delay from the SP report (Hammarström et al. 2008). In such a situation, there would be 9–20 of 46 people who delay evacuating and stay on the bus. This could have worsened the situation that needs to be considered.

Although some evacuees were injured in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) and took 161 s to evacuate the bus, all evacuees fortunately survived. However, only 23 people were involved. An increased number of people would lead to serious casualties. Therefore, the RSET and ASET based on a single fire incident needs to be carefully compared. In addition, the above comparison of the ECE (2006)’s study, the SP report (Hammarström et al. 2008), and

| Table 6. Comparison of RSET and ASET for tunnel safety assessment. |
|---------------------------------------------------------------|
| **Pre-evacuation time [sec]** | **Movement time (46 people) [sec]** | **RSET from bus [sec]** | **ASET (200 sec) – RSET** |
| ECE (2006) | 60–83 | 37–40 | 100–120 | OK |
| Present experiment and observation | 30 | 51–65 (Urgent) | 81–95 | OK |
| | 94–214 (Nonurgent) | 124–244 | 44 sec (9 people onboard) |
| | 60–83 | 51–65 (Urgent) | 111–148 | OK |
| | 94–214 (Nonurgent) | 154–297 | 97 sec (20 people onboard) |
| Hsuehshan tunnel fire incident | 30 | 131 (23 people) | 161 | OK |
| SP report (Hammarström et al. 2008) | | ASET from bus [sec] | 200–300 |
the Hsuehshan tunnel fire incident focus on the evacuation of a bus on fire. Since we studied a tunnel fire rather than a bus fire, smoke is an important a risk factor. Thus, whether bus evacuees can evacuate on time under smoke must be considered. Therefore, the risk assessment of tunnel fires involving a bus could be accurately determined by the flow rate of a nonurgent situation rather than that of an urgent situation.

Nonetheless, several limitations were associated with the present study. To maintain safety during the experiments, participants were chosen among fit, healthy, and able-bodied adults. However, the actual cases involved elderly and injured passengers. In addition, the uncertainties from participants (the variation from their thought and perception), uncontrollable changes in the experiment and observation conditions, and their contributions to the overall flow rate were not considered in this study. Moreover, we cannot ignore the following two phenomena in Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). First, almost one-third of the passengers evacuated the bus, the other two-thirds still stayed on the bus rather than evacuating continuously. Second, there is a considerable time gap between nonurgent and urgent situations, reducing the total flow rate in Figure 10 to as low as 0.17 PPS, much lower than the flow rate of the supposed nonurgent and urgent situations. These two phenomena reflect that the sort of two situations (nonurgent and urgent) is an explanation for bus evacuation in tunnel fire scenarios. Regardless, collecting more incident data for investigations on the mechanism of changes in bus evacuation situations and why some passengers delay evacuation is necessary.

For a reliable risk assessment of bus evacuation, a heterogeneous population (involving passengers with reduced mobility) needs to be considered. The present study has preliminarily pointed out that the time delay of passing a bus exit was approximately 7.2–43.9 s in the actual tunnel fire incident. A similar data range (6.2–25.4 s) was found in normal alighting observation. However, even though the data range in actual bus evacuation and normal alighting observation is similar, the causes are different. The time delay of passengers with reduced mobility, and the criteria for its determination still lacks a sufficient scientific basis. Considering bus evacuation is not necessarily a continuous process, further research is required to focus on the time delay for modeling bus evacuation time with high reliability.

6. Conclusions

We aimed to clarify evacuation flow rates from a bus for quantitative risk analysis of tunnel fires. We investigated flow rates from the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) and examined the two response types from this incident using two approaches, i.e. bus evacuation experiment, and normal alighting observation.

The analysis of the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017) demonstrated that an actual bus evacuation during tunnel fire is represented by two main responses: nonurgent (evacuees 1–7) and urgent (evacuees 8–19). Exit flow rates for the nonurgent and urgent situations were 0.28 and 0.67 PPS, respectively. In addition, although almost one-third of passengers evacuated the bus, others did not evacuate immediately. Additionally, considerable time gaps occurred in the evacuation process.

The bus experiment employing for simulating urgent evacuation found that the flow rates were approximately 0.69–0.88 PPS for a normal exit design (front and rear), and approximately 0.49 (in Japan experiment) and 0.68 PPS (in Taiwan experiment) for an emergency exit design. The flow rates in the experimental bus evacuation were close to those (emergency exit) for the second bus evacuee group in the Hsuehshan tunnel fire incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). Moreover, the emergency exit height (as installation position from the ground) in Japan was 1.4 m, so that the flow rate was smaller than other cases. This means that exits used for an emergency should consider the low height (as installation position from the ground) and ease of use to facilitate rapid evacuation.

The normal alighting observation employed a simulated nonurgent evacuation, which showed flow rates of normal exit (front) of approximately 0.21–0.48 PPS close to the flow rate for the first bus evacuee group in the Hsuehshan tunnel incident (Taiwan Area National Freeway Bureau 2013, 2016; Hsu et al. 2017). Moreover, some movement patterns resulting in irregular time gaps can be found in the present observation. Then, the discontinuous time distribution reduced the flow rate to a minimum of 0.21PPS. Relatively, the maximum flow rate was recorded for passengers alighting continuously.

Overall, nonurgent and urgent situations are expected to provide a viable approach in describing bus evacuation flow rates during tunnel fires. Moreover, because fire hazards are experienced far from the bus in a tunnel fire, it is regarded as a nonurgent situation when modeling their evacuation flow rates.

Nonetheless, we cannot ignore the fact that time delay affects the flow rate, reducing it to much lower than the flow rate of the supposed two evacuation situations (nonurgent and urgent). On the other hand, obtaining more information (i.e. the sight of flames, the smell of smoke, breathing difficulties, feeling the heat, and hearing the alarm or instruction) leads to a higher perception of risk and quick reaction of involved people.
However, the mechanism that can turn a nonurgent situation into an urgent situation has not been fully investigated. In the future, collecting sufficient data on time delay and the mechanism of changes in bus evacuation situations are necessary.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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