Dissertation

Walking speed and evacuation speed of the motorbike lane by considering the density of evacuees and motorbikes

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Cheng-Chung Cheng

1. Introduce

Tunnel spaces are the critical facility transportation system and mixed various vehicles, which are widely built and used as infrastructure for various countries. However, once a fire occurred in a road tunnel, hazards such as smoke, toxic gases, and high temperatures threaten the lives of users. A catastrophic incident would inevitably happen and cause difficulty in evacuation. Past tunnel fire incidents have revealed serious casualties [1–6] and pointed out the necessity of accurate risk assessment to establish strategies for reducing the consequences of fires.

To promote tunnel fire safety, researchers in Europe and Japan have been working on the clarification of evacuation behavior during tunnel fires and leading the field. The issues on evacuation safety involved the establishment of an evacuation safety assessment approach [7–8], the walking speed and behavior in the smoke with various extinction coefficient Cs [9–14], the speed in darkened tunnel environment with and without smoke [15–16], the speed in emergency evacuation scenario [17], the evaluation of the stress and connection to human behavior in tunnel evacuation[18], motorists' responses and emotional state [19], the influence of different way-finding installations on exit choice [10,11,12,20], and design of emergency exits [21–22]. Other countries have almost taken the risk assessment approach and safety criteria of Europe, and Japan as the reference for determining tunnel fire safety strategies. Since the proportion of motorbikes is small in Europe and Japan, the evacuation safety of motorbike users was not included in the risk assessment in the event of a tunnel fire.

However, in many Asian countries where the utilization ratio of motorbikes is extremely high, it is not uncommon for more than half of road users to be motorbike users. Studies on motorbike traffic in Taiwan, Malaysia, and Vietnam reported that the proportion of registered motorbikes in these countries was around 67%, 50%, and 90% of all registered vehicles in their countries [23–24]. Figure 1 is a scene of waiting for a traffic light in Taipei city in Taiwan. It reveals that the mix of many motorbikes and cars on the roads is a common phenomenon. Once a fire accident occurs in the tunnel in countries with a high utilization ratio of motorbikes, there would be a higher risk than expected due to the tunnel involving additional motorbike users who need to evacuate.

Figure 1 Scene of waiting for a traffic light in Taipei city in Taiwan

With our investigation of the tunnels which allow motorbikes to pass in Table 1, some motorbike lanes are designed not completely separated from the car lanes. Although motorbike users in these tunnels can move to the car lanes for evacuation, additional motorbikes and their users also increase the fire risk of motorbike accidents, extra hazards(fire, explosion, serious traffic accidents, etc.) to users in car lanes, and additional people who need to evacuate based on the perspective of the tunnel as a whole. Especially the Cross-Harbor tunnel in Kaohsiung City in Taiwan reflects a more dangerous situation for motorbike users as its special geometry. The motorbike lane of the Cross-Harbor tunnel is designed with a relatively high horizontal plane than the car lane which causes the motorbike lane to be influenced by fire and smoke relatively early. Figure 2 shows the height of the drop between the motorbike lane and the car lane in the Kaohsiung Crossing Harbor Tunnel. The distance from the upper end of the fence of the motorbike lane to the ground of the car lane is 2.75 meters, which is a dangerous height. Evacuees will not jump from the motorbike lane to the car lane to take evacuate. Moreover, the motorbike lane is independent in the tunnel. The difficulty in evacuation is that motorbike users have no choice but to evacuate to the portal through the motorbike lane. With the increasing utilization of motorbikes in some Asian countries, the number of tunnels available for motorbike passing will inevitably increase gradually. It is also possible to construct dedicated motorbike passages in the future, by considering traffic diversion to prevent traffic accidents (such as the Cross-Harbor tunnel in Taiwan). Based on the potential fire risk and evacuation restriction of the motorbike lane in tunnels, it is important to better understand evacuation behavior in motorbike lanes for preventing disastrous fatalities in tunnels with motorbike lanes

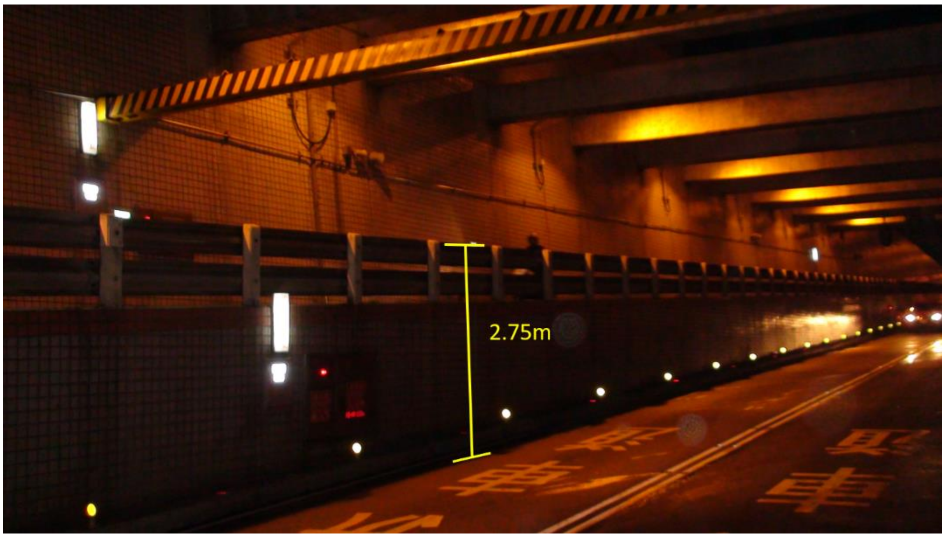


Figure 2 The drop height between the motorbike lane and the car lane

Regarding previous tunnel evacuation studies, tunnel users are usually assumed to decide to begin evacuating when they (1) see smoke along the ceiling or around them, (2) see other people evacuating, and (3) hear an emergency announcement walk speed [9], so that they may not begin evacuating as same time. Moreover, evacuees are considered not typically crowded in the tunnel space and can easily pass between vehicles on the road without difficulty because the car lanes are relatively large spaces (i.e., neither the vehicles nor other evacuees interfere with individual evacuee movement) [8]. However, take the Cross-Harbor tunnel as an example, its motorbike lanes are much narrow than the car lane and have a characteristic of heavy traffic. Inevitably, there would be many people and motorbikes in a small area. Moreover, motorbikes would obstruct evacuation behavior. The interference between motorbikes and evacuees is difficult to be neglected. Even if the interference between vehicles and evacuees causes a minor reduction in individuals' walk speed, the required total evacuation time would also increase significantly due to the long travel distance to the tunnel portal. Thus, it is critical to clarify the interference between motorbikes and evacuees. However, the research on interference between motorbikes and evacuees is still few.

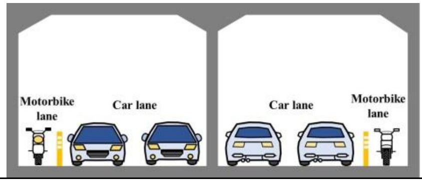
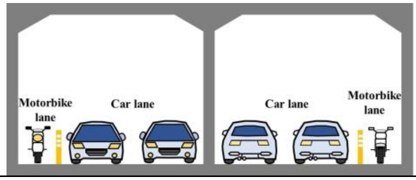
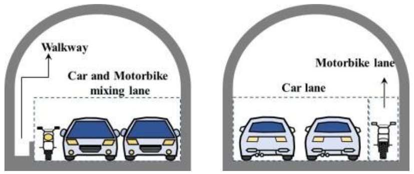
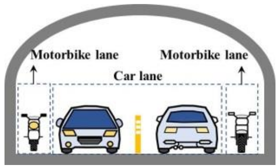
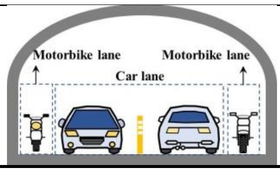
The studies on interference between evacuees (people) are usually in terms of clarifying the relationship between walking speed and human density (In the present paper, we called "human density" in the research of pedestrian facilities and buildings, called "evacuee density" in the motorbike lane evacuation.) [25–26]. Pauls (1987) studied building evacuation and pointed out that if the human density is less than 0.50–0.54 persons/m^2, individuals will walk alone at 1.25 m/s, independent of the speed of others. If the human density exceeds about 3.8 persons/m^2, no movement will take place [26]. Moreover, we also reviewed the experimental or observational literature regarding the relationship between walking speed and human density, in both pedestrian and building facilities in Table 2. Many studies on walking speed have been performed, including the investigation of walking speed characteristics of different pedestrian facilities [27–28], Modeling of the relationship between walking speed and human density[29–30], fundamental diagrams (speed-density relation, flow-density relation) of unidirectional and bidirectional flow [31–32], Estimating the level of service of pedestrian facilities [33], and investigation of walking speed on extreme high human densities [34]. Prior studies have well-investigated general motion parameters, such as the total crowd flow rate and the overall speed of crowd movement. Many diagrams have also been established for describing the relationship between walking speed and human density. However, most studies of the speed-density relationship focused on the normal walking movement of pedestrians, rather than evacuation scenarios in tunnels. Human density is mainly ranged in over 1 person/m^2 or a null speed (i.e., speed close to 0 m/s) at which people cannot move.

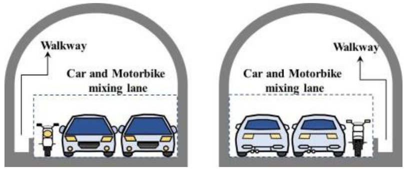
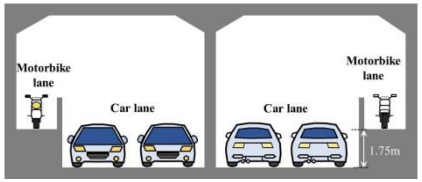
On the other hand, the maximum evacuation speed is an especially important parameter to understand because it reflects the difference in quickness between the awareness of non-urgent and urgent situations during evacuation. Simultaneously, the raise in evacuation speed could also be a trigger or a kind of conveyance of information to shorten the time required to start the evacuation for other evacuees.

Motorbike lanes in the tunnel have the characteristics of narrow width, hundreds of meters distance, and the obstruction of motorbikes. The human density is relatively low as is not designed for dense crowd passing. Whether existing diagrams of speed-density and developed models could completely describe the walking speed characteristics in motorbike lanes is unclear. Therefore, the present study aimed at developing an evacuation model which considered the effect of motorbike density and evacuee density on the walking speed and evacuation speed of motorbike users. The problems to be addressed are as follows. Will the walking speed or the evacuation speed decrease with motorbike density and evacuee density? If yes, how much does the walking speed or the evacuation speed decrease? If these things are clarified, it would help develop the sub-evacuation model which can be applied to analyze the event of a tunnel fire in countries with a high motorbike utilization rate, and possibly to further improve the safety assessment process for tunnel fires. Considering the relatively higher danger due to the geometry of the Cross-Harbor tunnel, the present study chose the motorbike lane in the Cross-Harbor tunnel as the model and conducted evacuation experiments in modeled motorbike lane in an underground walkway. The experimental studies were carried out to discuss the effect of motorbike density and the evacuee density.

The second chapter of the present study uses the Kaohsiung Crossing-Harbor Tunnel as a model to construct an experimental site in the underground passage of Chiayi Chang Gung Hospital. Experiment with different gender and age bracket of experimenters and different scenarios (normal walking speed and evacuation speed), and record the through time of each experimenter case in different experimental sections and different scenarios, so as to compare the speed between evacuee's density and motorbike's density correlation analysis. The third chapter uses the least squares method to analyze the normal walking speed correlation between the evacuee's density and the motorbike's density, and proposes a regression equation. In the regression equation of evacuee density and normal walking speed, a two-regime method is used to connect the evacuee low-density and the high-density equation. And the equation of this two-regime model is evaluated by RMSE method as the best evaluation model, and finally, some research limitations are proposed. The fourth chapter analyzes the evacuation speed relationship between evacuee's density and motorbike's density by the least square method, and proposes the regression equation respectively, and finally puts forward some research limitations. The fifth chapter puts forward some conclusions according to the research results of each chapter.

Table 1 Road tunnels that can pass motorbikes.

Tunnel name	Cross section	Tunnel length	Country	Independent lane for motorbikes	Motorbike height (from the ground)	Motorbike Traffic flow	Four-Wheeled Vehicle Traffic Flow
Qiao-Zhong Road Tunnel		295 m	China	Yes	0	–	–
Saigon River Tunnel		1490 m	Vietnam	Yes	0	–	–
Zi-Qiang Tunnel		820 m	Taiwan	Yes	0	602/hour1	187/hour[1]
Da-Hu Tunnel		519 m	Taiwan	Yes	0	–	-
Kang-Le Tunnel		586 m	Taiwan	Yes	0	-	-

Xin-Hai Tunnel		490 m	Taiwan	No	0	1515/ hour1	139/hour[1]
Cross-Harbor Tunnel		1670 m	Taiwan	Yes	1.75 m	1160/ hour	1270/ hour

Note: Motorbike traffic flow means the number of motorbikes passing the tunnel during rush hour

[1] Reference from Taipei City Traffic Control Engineering Office, Survey of Traffic Flow and Characteristics in Taipei City in 2017 (uni-direction traffic flow in rush hour)

Table 2 Literature review on walking speed and speed-density relation in experimental or observational studies

Item	Oeding (1963) [28]	Mōri and Tsukaguchi (1987) [33]	Virkler and Elayadath (1994) [30]	Seyfried et al. (2005) [31]	Helbing et al. (2007) [34]	Zhang and Seyfried (2013) [32]	Das et al. (2015) [29]	Rastogi et al. (2013) [27]	Present study
Scenario	Uncontrolled walking (Commuters)	Uncontrolled walking (Commuters)	Uncontrolled walking (After watching a football game)	Controlled normal walking	The scene of the Muslim pilgrimage	Controlled normal walking	Uncontrolled walking	Uncontrolled walking	Evacuation assumption (Assume as a commuter)
The direction of the human flow	Bidirectional	Bidirectional	Unidirectional	Unidirectional	Unidirectional	Both Unidirectional and Bidirectional	Bidirectional	Bidirectional	Unidirectional
Density range [person/m^2]	0.16–2.61	0.11–6.07	0.16–3.14	0.75–4.29	1.16–9.90	0.06–3.93	0.01–1.58	0.02–2.32	0.05–0.56
Methodology	Observation	Observation	Observation	Experiment	Observation	Experiment	Observation	Observation	Experiment
The geometry of walking space	Shopping streets, footpaths along company buildings, etc.	Side walkway and underground walkway (Length: 20 m; Width: 2.2–4.5 m)	A walkway (Length: 12 m; Width: 8.5, 10, 12, and 13 m in four 3-m sections)	A circular passageway (selecting 2 m of the straight part of the passageway; Width: 0.8m)	A large area (Length: 27.7 m; Width: 22.5 m)	Straight corridor (Width: 1.8, 2.4, and 3.0 m), closed ring, T-junctions , and around a corner.	Sidewalks and carriageways around transport terminals (Observation section: Length: 10 m; Width: 2.7 m)	Sidewalk (Width:1.6–4.0 m)	Modeled motorbike lane (Length: 50 m; Width: 2.6 m)
Number of	–	–	–	Six cases	–	Up to 400	418 (Sidewalk)	674	40

participants				(Subject No. = 1, 15, 20, 25, 30, 34)		people			
Age	–	–	–	–	–	19.3–30.7	–	–	25–61

Nomenclature

$f(\rho_e)$	Influence of evacuee density to walking speed or evacuation speed
$g(\rho_b)$	Influence of motorbike density to walking speed or evacuation speed
ρ_e	Evacuee density = $1 / (wV\Delta t_n^{k,k+1})$ [unit: person / m^2]
ρ_b	Motorbike density = $N / (wL)$ [unit: motorbike / m^2]
N	Motorbike numbers [unit: motorbike].
w	Motorbike lane width [unit: m].
$\Delta t_n^{k,k+1}$	Individual time interval in specific section [unit: s].
ΔT	The starting interval time= 1s, 2s, and 3s.
T_n^k	The time point when the n-th subject pass the checkpoint k [unit: s].
V	Walking speed or evacuation speed = L / T [unit: m/s]
V_0	Denotes a walking speed or evacuation speed that is not affected by the evacuee density and motorbike density
L	The measured section length in motorbike lane [unit: m].
T	The time elapsed for the subject pass through a specific section[unit: s]

2. Motorbike Lane evacuation experiments

2.1 Design of Experiments Literature Review

To investigate the influence of evacuee density on walking speed in the motorbike lane, the present experiments simulated the behavior of individual evacuees in a 2D space that features motorbike lane characteristics. In motorbike lane evacuation, evacuees typically need to stop their motorbike and evacuate toward the opposite direction of the motorbike's direction of travel in the event of an emergency. At that time, evacuees must walk in the narrow motorbike lane. Individuals are expected that they would move in one direction to the portal. However, compared with walking in car lanes, the difference is that accumulated motorbikes in the tunnel would form obstacles, causing a relatively crowded condition than in car lanes. As for the degree of influence? And how to model the walking speed in such a situation is an issue necessary to be clarified.

Thus, before investigating the walking speed in the scenario on which the present study focuses, we reviewed the past studies related to the speed-density model in the pedestrian flow field. Most of the well-known speed-density models are listed in Table 3.

Table 3 Deterministic speed-density models applied in pedestrian flow.

Model name	Function	Definition of terms
Greenshields's Model (1935) [35]	$V = V_f\left(1 - \frac{k}{k_j}\right)$	V_f : Free flow speed V_m : Optimal speed k : Observed density k_j : Jam density
Greenberg Model (1959) [36]	$V = V_m \log\left(\frac{k_j}{k}\right)$	

Underwood Model (1961) [37]	$V = V_f\ e^{-\frac{k}{k_o}}$	k_o : Optimal density (density with the maximum flow or capacity)
Kladek Model (1966) [38]	$V = V_f \left[1 - e^{\left(\frac{1}{k} - \frac{1}{k_m}\right)}\right]$	k_m : Maximum density as speed was zero
Drake's Model (1967) [39]	$V = V_f\ e^{-\frac{1}{2}(\frac{k}{k_j})^2}$	

The proposed speed-density models in Table 3 reveal that the linear and exponential models have been used to describe the relation between speed and humans for crowd movement, considering the free walking speed (i.e., walking speeds when people are not influenced by other nearby people.) and different density conditions[35–39].

On the other hand, Seyfried et.al (2005) ever pointed out that there is a small and increasing decline in walking speed at low densities (density < 0.7 person/m^2) [31]. The speed is mainly determined by the individual free velocity of the pedestrians. The passing maneuvers cause a decrease in walking speed. Pauls, J. (1987) indicated that individuals would walk alone at 1.25 m/s, independent of the speed of others when human density is less than 0.50–0.54 persons/m^2 [26] in building evacuation. There are various opinions on walking speed in low-density conditions. And the influence of the interference between adjacent people on walking speed in low-density conditions seems still lacks sufficient investigation. The reason could be that the occupied area required by the individual walking process is usually deemed sufficient when the human density is low, so the speed in the low-density condition is considered determined by the individual's free walking speed. However, the research of Bruno and Venuti (2008) on the relationship between speed and density has mentioned that the required area for walking depends on the required width (*w*) and the required forward distance (*l*). And required forward distance(*l*) can be expressed as the sum of two terms: the step length(*lp*) and the sensory distance(*ls*), while the former can be physically measured, the latter depends to a great extent on cultural and psychological factors [40]. In Thompson et al. (2020)'s study, a similar concept of sensory distance(*ls*) was defined as the "contact buffer" [41]. Thus, the influence of interference between people during evacuation must be considered when the analysis of walking speed is aimed at the crowd rather than the individuals.

In some tunnel experiments in the past (seike et al 2021, fridof.et al 2013, fridof.et al2015, seike.et al 2016)[17,12,14,9], in the process of researching tunnel escape, there were placed solid cars as obstacles, and tents were also used as barriers. obstacles, but they are all tested in the tunnel car lane. The tunnel motorbike lane is hundreds of meters long and several meters wide, and there is no emergency exit. motorbikes stopped on the tunnel motorbike lane during the evacuation process will form obstacles and hinder evacuation. However, it is not known how much the specific motorbike density will cause the disturbance of the evacuation speed. Therefore, the impact of motorbike interference must also be taken into account during the evacuation process of the tunnel motorbike lane.

Chung et al. (2020) classified the bus alighting behavior of evacuees in the 2012 Hsuehshan tunnel-fire incident as non-urgent and urgent, the latter mainly referring to the speedy action, i.e., running or quick movements, a second group of evacuees took after a first group (who did not necessarily haste) alighted the bus.**[**42**]** The motion speed of an evacuee can convey crucial information affecting the decision of other evacuees, such as running initially then shifting to semi-jogging (Seike et al., 2016, 2017a) [9,8], in the absence of an emergency announcement. Here, the speed of information transmission from one evacuee to another shortens the time required to start the evacuation (Seike et al., 2017b) [15].

In the evacuation model proposed in the paper (Seike et al., 2011)[7], people start to evacuate when they see smoke or other people evacuating or hear emergency announcements, and after recognizing that they must evacuate, they evacuate at a constant walking speed. Hence walking speed during evacuation is not just the moving speed of evacuees but is also affected by the speed of information exchange, which alerts people to the need for evacuation. Thus, the maximum evacuation speed is one of the most important factors to consider to assess tunnel fire safety.

In table 4 that we studied in the previous experiments, we selected several experiments related to tunnel evacuation speed for analysis. Some experiments investigated normal walking speed, some investigated emergency evacuation speed, and some investigated two different speeds(normal walking and emergency evacuation speed). Some experiments had vehicle obstacles and some did not. Some experiments are performed in a no-smoke environment, some experiments are performed in a smoke-filled environment, or hypothesized to be in a toxic gas and explosion hazard environment. Most of the experiments are focused on the tunnel car lane experiments. Our experiment is to simulate the space of the tunnel motorbike lane by the underground passage; and investigate the normal walking speed and emergency evacuation speed of the tunnel motorbike lane with different evacuee densities and motorbike densities. In particular, it focuses on the impact of evacuee density and motorbike density on walking speed and evacuation speed, which is different from previous experiments.

Table 4 General Situation of Tunnel Evacuation Speed Experiment

Item	Seike et al(2021) [17]	Seike et al(2020) [16]	Seike et al(2016) [9]	Fridof (2013) [12]	Fridof (2015) [14]	Bore (2001) [52]	Present study
Experimental space	Physical tunnel	Physical tunnel	Physical tunnel	Physical tunnel	Physical tunnel	Physical tunnel	Underpass (simulated tunnel motorbike lane)
Experimental situation	■ Normal walking scenario ■ Emergency evacuation scenario	Normal walking scenario	■ Normal walking scenario ■ Emergency evacuation scenario	Normal walking scenario	5 different walking scenarios	Emergency evacuation scenario	■ Normal walking scenario ■ Emergency evacuation scenario
Experiment purpose	Quantitative assessment using evacuation velocity in diffuse smoke	Measuring walking speed in a total darkness tunnel	Investigating the effect of smoke and obstacles on walking and evacuation speeds in tunnels	Investigating the normal walking speed for evacuation under different smoke concentrations and vehicle obstacles	Measuring walking speed and finding emergency exits in smoke-filled and no-smoke areas of tunnels	Investigate emergency evacuation speeds assuming tunnels filled with toxic gas and explosion hazards	Investigate the normal walking speed and evacuation speed of the tunnel motorbike lane under different evacuee density and motorbike density
Obstacle	There are vehicle obstacles	no	5 obstacles	6 vehicle obstacles	4 vehicle obstacles	no	10 motorbikes
Smoke or other gas or	there is smoke	Smoke filled tunnel	No smoke and 3 different smoke	There is smoke	No smoke and smoke	Assuming tunnels filled	No smoke and assuming a fire in

hazardous conditions			concentrations			with toxic gas and explosion hazards	the tunnel and a risk of explosion
Participant	1019 (756 male, 263 female)	306(171male, 135female)	294(normal:164,evacuation:130)	133	65	69	40(20 male,20 female)

2.2 Experiment conditions and process

After comparing the structure of the tunnel (see Table 1) can find that the motorbike lane in the Cross-Harbor tunnel in Kaohsiung City, Taiwan is installed 1.75 m(2.75 meters from the top of the motorbike lane fence to the ground of the car lane) higher than the car lane, and it is designed as an independent lane for motorbike users (see Fig. 3). The thermal fume of a fire flow along with the tunnel ceiling, causing the motorbike lane with a relatively high horizontal plane to be influenced earlier by fire and smoke and requiring faster evacuation. The independent motorbike lanes also cause motorbike users no way to evacuate from the motorbike lanes to the car lanes but to evacuate to the tunnel portal through the motorbike lane. The higher risk of evacuation caused by the special geometry is necessary to be considered. Thus, the present study chose the motorbike lane in the Cross-Harbor tunnel as the model.

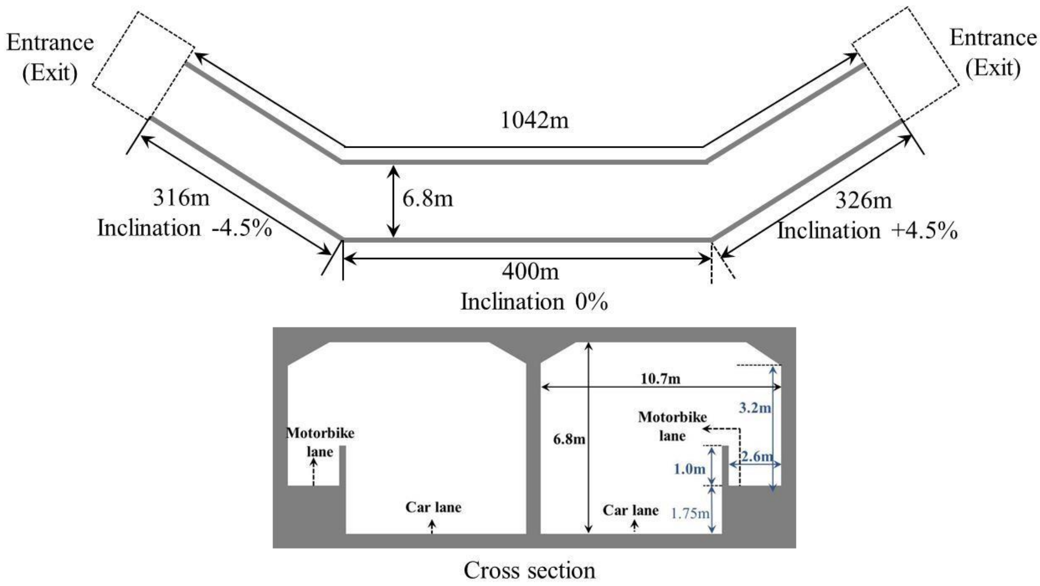


Figure 3 Cross-Harbor tunnel geometry

Although the experiment hoped to be conducted in an actual tunnel with a motorbike lane. However, there would be some problems such as road traffic control when conducting experiments in the real tunnel which is in operation. Therefore, an underground walkway was chosen as the experiment space for modeling the motorbike lanes in the present study. The underground walkway is in the Chiayi Chang Gung Memorial Hospital in Taiwan. The experiment was conducted on July 1, 2017

The underground walkway is around 60 m long, and 5.5 m wide. Fig. 4 shows the experimental place (consisting of longitudinal intervals and transverse sections). We supposed the underground walkway has two motorbike lanes with a width of 2.6 m and a length of 50 m. And each lane was divided into three sections (see Fig. 5). To ensure the walking speed is stable when the subjects passed the area with the motorbike, we set up the non-motorbike sections in front and rear of the motorbike section to avoid subjects suddenly moving and stopping during passing the section with motorbikes

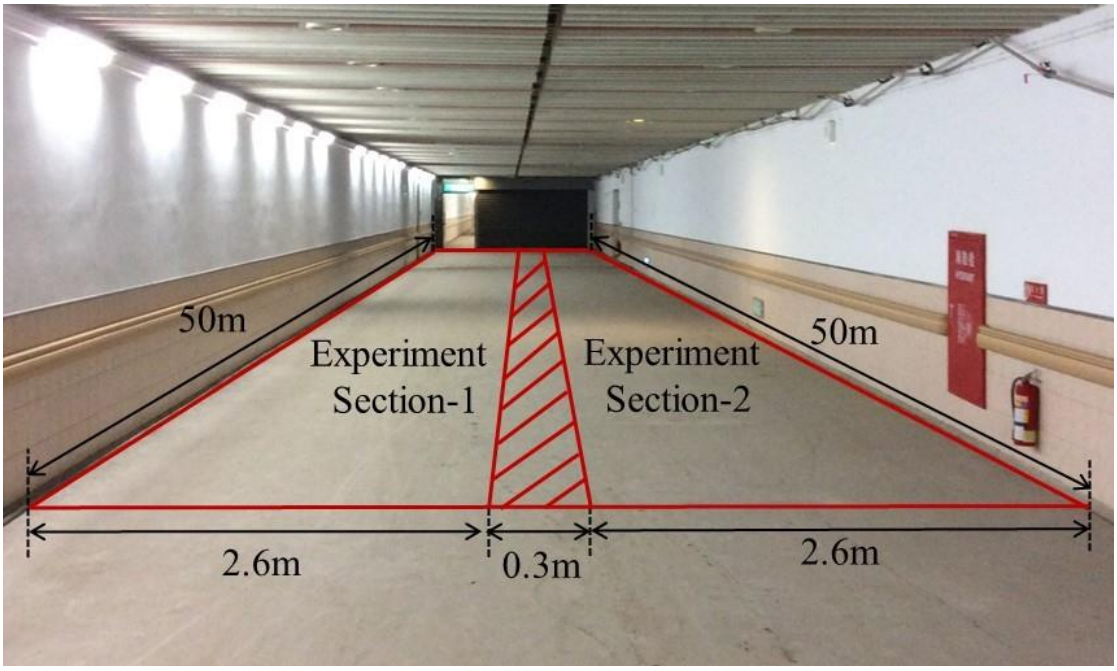


Figure 4 Evacuation experiment place.

In the present study, an underground walkway was chosen as the experimental site to reflect a motorbike lane. Nevertheless, there exist some differences between the assumed motorbike lane and the real motorbike lanes of the Cross-Harbor Tunnel, as outlined in Table 5.

Table 5 Differential analysis of assumed motorbike lane and real motorbike lane in Cross-Harbor Tunnel.

	Assumed motorbike lane (underground walkway)	**Real motorbike lane (in Cross-Harbor Tunnel)**
Geometric	Length 50 m; width 2.6 m	Length 1042 m; width 2.6 m
Inclination	0%	−4.5%, 0%, 4.5%
Evacuation scenario	■ Evacuate only occurs using the lane in the experiment. ■ Subjects only bypass stationary motorbikes, resulting in less risk of collision or injury.	■ Evacuation only occurs using the motorbike lane (no car lanes can be used). ■ Evacuees might encounter moving motorbikes,

		increasing the risk of collision or injury.
Evacuation direction	Instructed to be in only one direction.	Without instruction, evacuation in both directions is possible.
Evacuee density	Controlled by experiment setup.	Variable (depending on situation).
Motorbike density	Controlled by experiment setup.	Variable (depending on situation).

As shown in Table 5, the chosen experimental site reproduced the real motorbike lane geometry in terms of width, flat region in the partial motorbike lane, and the difficulty of evacuation in that subjects had no choice but to evacuate to the portal through the motorbike lane. The evacuation scenario regarding subjects bypassing motorbikes was investigated through controlled evacuee and motorbike density.

As demonstrated in Figure 5, subjects wore the numbered vest and were asked to orderly start to walk (according to the vest number) from the start line to the finish line (CP_1 to CP_4) to complete an experiment case. And then, subjects were requested to return in the negative *x*-direction according to the staff's instructions to start evacuation from another start line to the finish line (CP_5 to CP_8) to complete the next experiment case (see Figure 5).

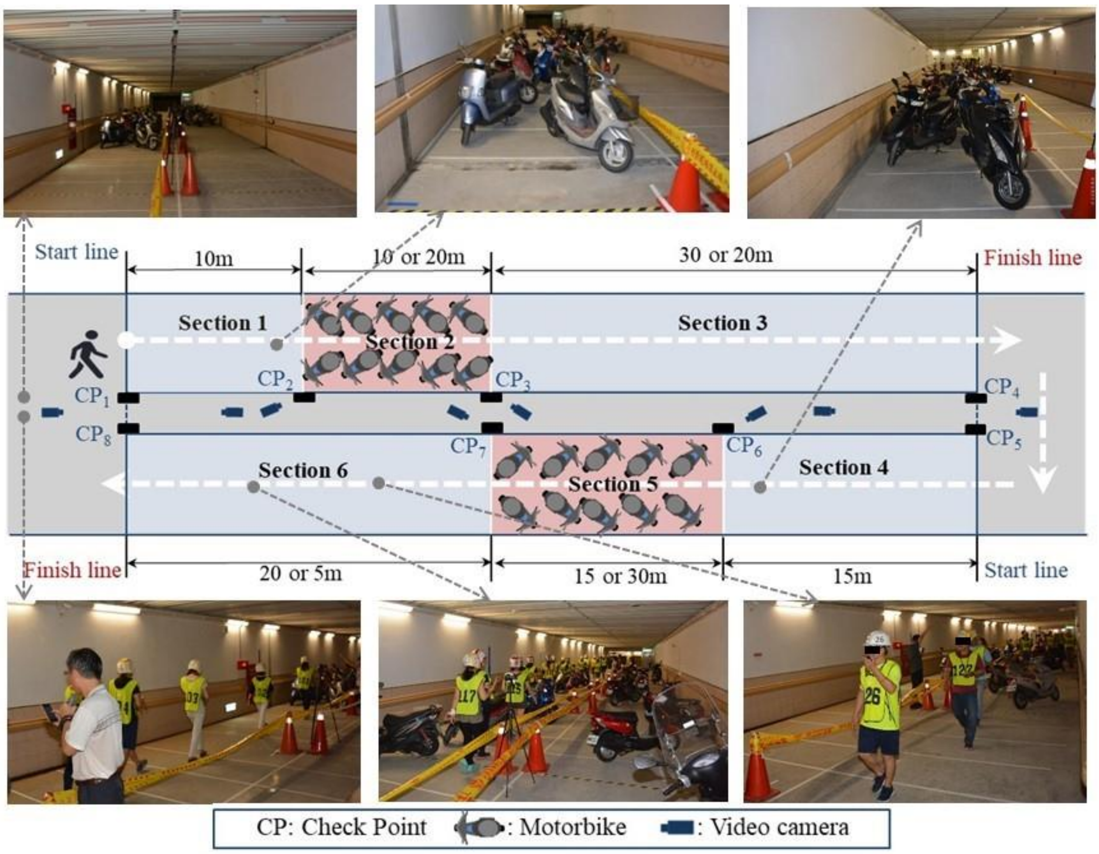


Figure 5 Schematic of motorbike lane experiments.

Typically, users involved in tunnel fire incidents decide to begin evacuating when they (1) see smoke along with the ceiling or around them, (2) see other people evacuating, and (3) hear an emergency announcement [8]. In the present study, we divided the experimental study into two scenarios, the first one is the normal walking scenario, and the other is the evacuation scenario.

In the normal walking scenario, we focused on clarifying normal walking speed to investigate the basic evacuation performance characteristics in an emergency such as fire rather than maximum evacuation speed considering the extremely urgent condition (i.e., people may jog or semi-jogging). To reproduce the evacuation situation with a purposeful movement characteristic, participants were instructed to walk based on the oral explanation in the present experiments. The explanation was given as follows.

"Please walk in the tunnel as you normally walk, such as the situation of going to the company to work" (the situation hoped to reproduce the situation that subjects walk at the state who have a clear destination, not aimlessly).

Ensuring a quick evacuation in tunnels is the most important concern for the authorities of tunnel management. To assess safety during a tunnel fire, Seike et al[16] have pointed out that is essential to establish the three main evacuation speed parameters: (1) Maximum evacuation speed, (2) Medium evacuation speed, and (3) Minimum walking speed. The motion speed of an evacuee can convey crucial information or a trigger affecting the decision of other evacuees, such as running initially then shifting to semi-jogging [8,9], in the absence of an emergency announcement.

Here, the speed of information transmission from one evacuee to another shortens the time required to start the evacuation[15]. In the present study, we focused on reproducing the evacuation speed which is relatively close to the maximum value representing an important parameter to understand the evacuation behavior. To reproduce the evacuation situation, participants were given instructions throughout the duration of the experiment. The explanation was given as follows.

"Fire occurs in the tunnel and the present situation is considerably serious that an explosion could occur or the fire might spread, so please decide to evacuate, and do extremely urgently."

The speed of the two situations(normal walking speed and evacuation speed) were calculated based on the time passed between checkpoints. Checkpoints (CP) were set by the triangular cone and masking tape on the floor. Subjects measured the passing times themselves by pushing the lap time buttons of the stopwatches they carried. To prevent the data did not being successfully recorded as the participant forgot to press the stopwatch, the present experiments also placed six video cameras to record the evacuation process. In addition, the present experiments don't consider the hazards of fire and smoke. One reason hopes to ensure the safety of the subjects. Another reason is that the present experiments hope to clarify the evacuation situation that the smoke layer has not yet descended to affect the evacuation path, rather than walking in smoke-filled conditions.

To investigate the characteristics of the walking speed of motorbike users in the tunnel, we considered two factors that might affect the walking speed of subjects in the present study. One is motorbike density, and another is the evacuee density. The detailed consideration regarding these two factors was described in the following section.

2.3 Motorbikes setup and density calculation

Since motorbike lanes are narrow, a scenario that needs to be noticed is that motorbikes would obstruct evacuation behavior if a traffic incident occurred in the motorbike lane and then a secondary accident occurred with fire after the location of the first accident. Thus, the interference of motorbike densities would be a critical factor to influence the walking speed. To grasp the characteristics of motorbikes density especially the congestion situation in an emergency, a record of the past traffic accident that occurred in the motorbike lane in the Kaohsiung Cross-Harbor Tunnel was analyzed. According to the video record, motorbikes stopped behind the accident point, and the motorbike that arrived later would also stop after the accident point one after another and accumulated slowly. We counted the number of accumulated motorbikes with an interval time of 30 s after a traffic accident occurred in the motorbike lane within 5 min (as shown in Fig 6)

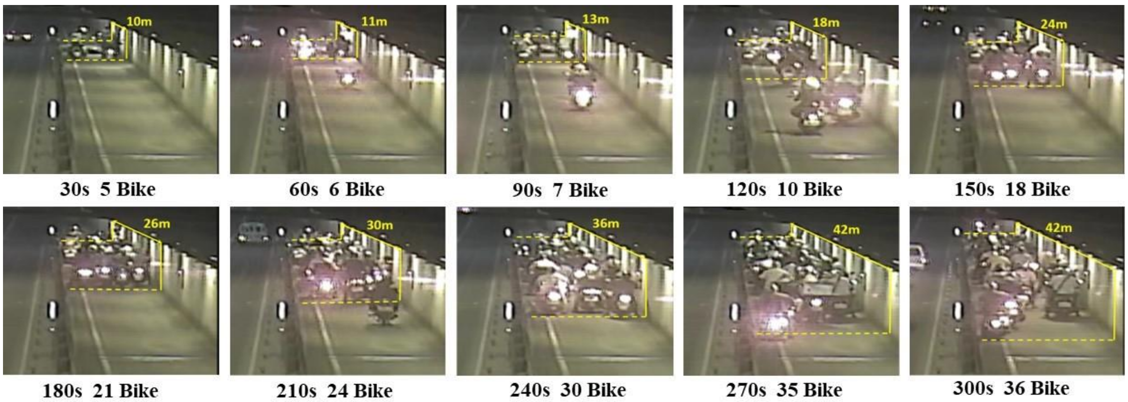


Figure 6 Screenshot of a real traffic accident in the motorbike lane (Data source: Taiwan)

In Figure 6, we considered the sidewall lamp post as the starting point to calculate the distance of the motorbike stopping with time. The distance between the lamp post and the lamp post is 7 meters, so the total length of the stopped motorbike can be calculated based on the corresponding lamp post. The distance of the accumulated motorbike was defined as the straight length of the stopped motorbike along the direction toward the portal of the tunnel. The cumulative number of motorbikes was defined as motorbikes that stopped in the lanes over time (excluding the moving motorbikes). The accumulated distance and cumulative numbers are shown in Table 6.

Table 6 The cumulative motorbikes in a real traffic accident

Cumulative time [s]	Cumulative number of motorbikes	Distance of accumulated motorbikes [m]
30	5	10
60	6	11
90	7	13
120	10	18
150	18	24
180	21	26
210	24	30
240	30	36
270	35	42
300	36	42

On the other hand, we also counted the real traffic flow rate in the motorbike lane in the Cross-Harbor tunnel in Kaohsiung city in Taiwan on January 18, 2016 (see Table 7). We observed that the flow of motorbikes was around 0.26 – 0.36 [motorbikes/s] (mean: 0.32 motorbikes/s) during the rush hour (7:00 am– 8:00 am). Table 7 reveals that the worse evacuation scenario would be in the motorbike flow rate of around 0.35 [motorbikes/s] because it lasts for about 40 minutes during rush hour. Comparing the traffic flow in a real traffic accident in Table 6 reveals that the motorbike flow rate in a traffic accident (36/300=0.12 motorbikes/s) was only around one-third of the flow rate in rush hour. It implies that once the incident occurs in the tunnel during rush hour, there would be adding three times as many motorbike users stranded inside the tunnel, compared to this real traffic accident. Therefore, it can expect that the difficulty in the motorbike lane evacuation would also increase once the fire occurs during rush hour.

Table 7 Traffic flow of Cross-Harbor tunnel motorbike lane during rush hour (Date: 2016.1.18)

Time	**7:00–7:10**	**7:10–7:20**	**7:20–7:30**	**7:30–7:40**	**7:40–7:50**	**7:50–8:00**	**Total**
Number of Motorbikes	157	214	208	205	211	165	1160
Number of Passengers	177	232	219	214	222	174	1238
Motorbike flow rate [motorbike/s]	0.26	0.36	0.35	0.34	0.35	0.28	0.32
Passenger flow rate [person/s]	0.30	0.39	0.37	0.36	0.37	0.29	0.35

Moreover, we further show the cumulative motorbike number and corresponding accumulated distance in Figure 7. The distance of stopped motorbikes increased with the cumulative number of motorbikes, and the tendency presented a linear regression function ($y = 0.98x - 5.42$). The linear function in Figure 7 also reveals that the distance would be 5.42 m ($x= 5.42$) when no motorbike stopped ($y= 0$), which means that the first motorbike stopped far away around 5.42 m from the starting point of the calculation (sidewall lamp post).

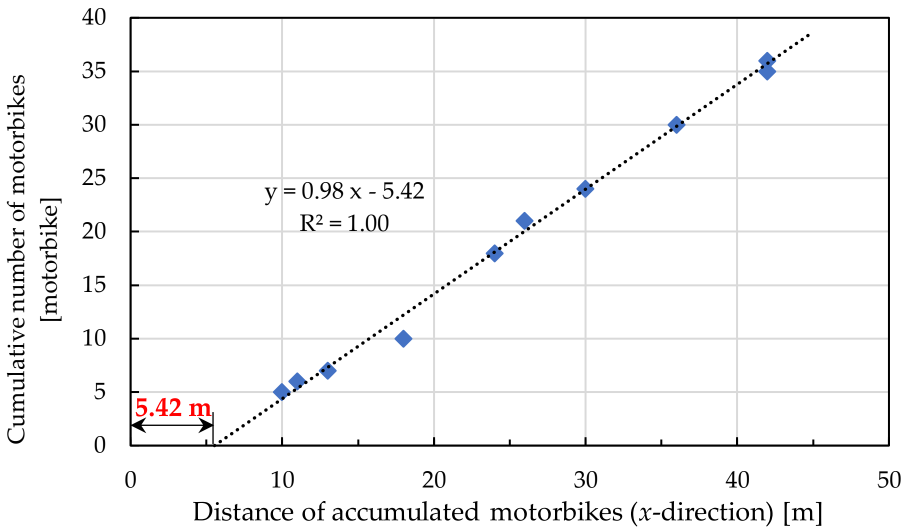


Figure 7 The cumulative motorbike number and corresponding accumulated distance.

In addition, the slope of the linear regression function of 0.98 means that around 0.98 motorbikes park in the lane per meter. And the slope divided by the motorbike lane width (2.6 m) was 0.38 motorbikes/m^2. The result of linear regression relatively indicates that the density of stagnant motorbikes would be a constant value independent of the time, and the value was close to 0.38 motorbikes/m^2. As a result, based on the investigation of the real traffic accident in the motorbike lane, we set up a motorbike density condition close to the real situation (0.38 motorbikes/m^2). Considering the possibility of tunnel motorbike lanes with different densities of congested motorbikes due to fires or other traffic accidents, we also assumed other relatively lower motorbike densities for the experiments. Considering the safety of the experiments, motorbikes are assumed to have a stationary status rather than an operating status to avoid the danger of collision.

As demonstrated in Figure 5, we set up 10 motorbikes in the motorbike section (see the red section in Figure 5) in the experiments. The section lengths parked with motorbikes were set up as 10 m, 15 m, 20 m, and 30 m. Motorbikes were evenly located in the section. Therefore, the motorbike density would change with the section lengths. The density would be controlled at 0.38, 0.26, 0.19, and 0.13 [motorbikes/m^2] respectively. To genialize the calculation process, the motorbike density (ρb) was further expressed as $\rho b = N / (wL)$ by considering the section lengths (L) and motorbike lane width (w).

2.4 Experiment subjects and density calculation

Motorbike lanes in the tunnel have the characteristics of several meters in width, hundreds of meters in length, obstruction of motorbikes, and relatively low human density. Whether the existing model for pedestrian flow or building evacuation can completely explain the walking speed characteristics in motorbike lanes is unclear. Especially how the influence of the interference between adjacent people on walking speed even in a low-density state. Since the present study focused on the scenario in which evacuees walked in the motorbike lane, it was expected that the interference between evacuees would also be a critical factor even when the evacuee density is relatively low. Thus, to investigate the effect of the interference between adjacent evacuees on the walking speed of tunnel evacuation in the low human density condition, we instructed the subject to start walking after the previous subject has walked at around 1 s, 2 s, and 3 s later. And this instruction was informed to the subjects at the start line (CP1 and CP5) in Fig 5.

To minimize the number of variables to be considered in the walking speed model, we embed the concept of "interference between adjacent evacuees" into the variable of evacuee density. Regarding the density calculation, we consider the width of the motorbike lane rather than only the required lateral space for walking. Thus, the influence of the interference between adjacent evacuees would mainly be reflected by the change in evacuee densities.

It should be noted that the real-time interval between adjacent subjects would dynamically change with time when they walked through each section in the experiment region. Therefore, to distinguish the difference, we called the time difference that instructs subjects to start walking “starting interval time” and called the time difference between adjacent subjects in walking “time interval” in the present study. The time intervals between adjacent subjects would change the distance between subjects and thus change the density of subjects in the motorbike lane. The detailed calculation from the “time interval” into “evacuee density” is described in the following Section 2.5.

Regarding the composition of the subjects, there were 40 subjects (20 male and 20 female) in the present experiments. The age bracket of 30 years old or younger, 30 to 40 years old, 40 to 50 years old, and 50 years old or older was 5 males and 5 females, respectively. Since the present experiments focused on the investigation of walking speed in different evacuee densities, the influence of different ages and genders was not further explored. Furthermore, by observing the walking speed (including the mean and 95% confidence interval) of males and females (starting interval time designed as 1s、2s、3s) in the present experiments (see Fig. 8、9、10) can find that the influence of age and gender has the difficulty in clarification. Even appeared as an unnatural situation where females walk faster than males. The results reflect that the influence of the different ages and genders could not be observed in the present experiments. Therefore, the experimental results in the next section would only focus on discussing the relationship between walking speed and evacuee density.

Why does this happen? Regarding the experiment process, the order of start walking is designed as younger female, older female, younger male, and older male sequentially. The female group walking first is hoped to avoid the situation that males walking fast and the distance between males and females would be too long resulting in the topical evacuee density unevenness. And the younger female and male walking first is hoped to avoid overcrowding in the female group (or male group) so that the time interval deviates from the conditions of experimental design. Since the first few female subjects who started walking were not affected by others and walked fast, we excluded the data of the first five subjects when analyzing the walking speed. From the experimental results, the time interval of the other 35 subjects were indeed controlled at around the "starting interval time" of 1s, 2s, and 3s.

However, such experiment design rather results in an additional unexpected situation that younger males (relatively move fast) are obstructed by older females (relatively move slowly). And revealing the walking speed of younger males is close to older females in Figure 8、9、10. Therefore, we consider the possible reason for the above-unexpected situation is related to the order of start walking. It relatively implies that the influence of age and gender was difficult to clarify in the present experiment.

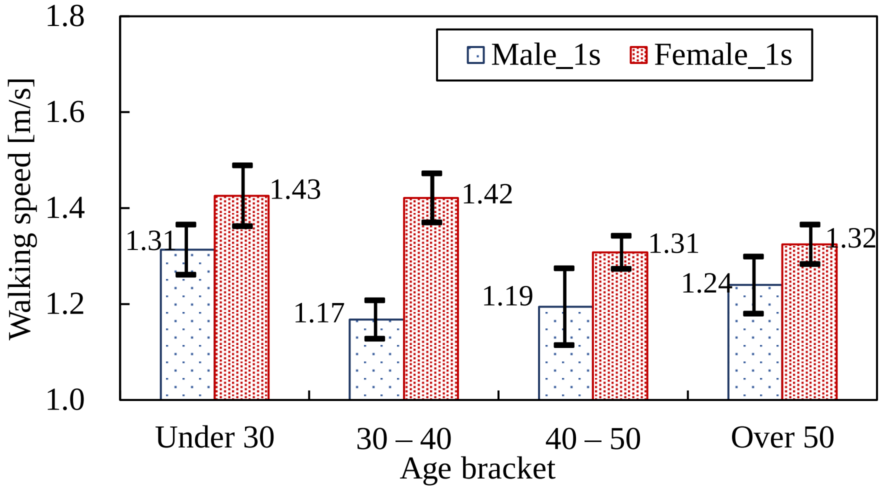


Figure 8 Walking speeds in the no motorbike section(1s)

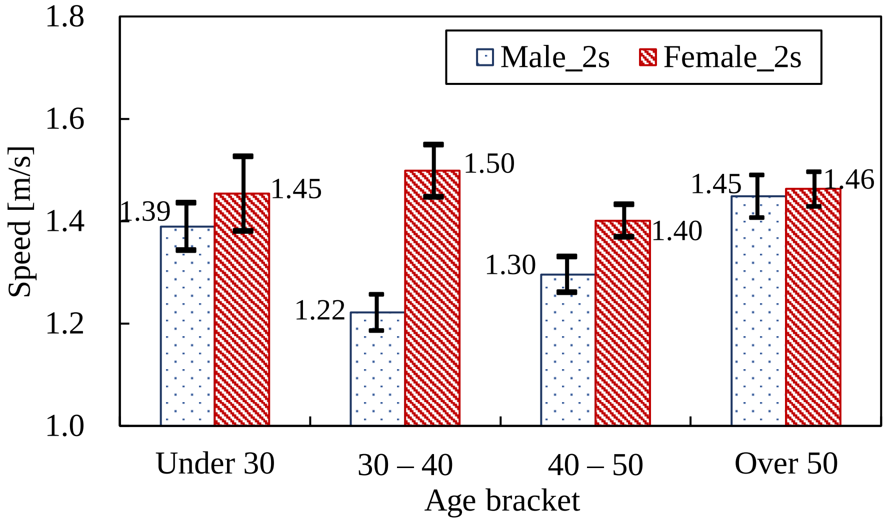


Figure 9 Walking speeds in the no motorbike section(2s)

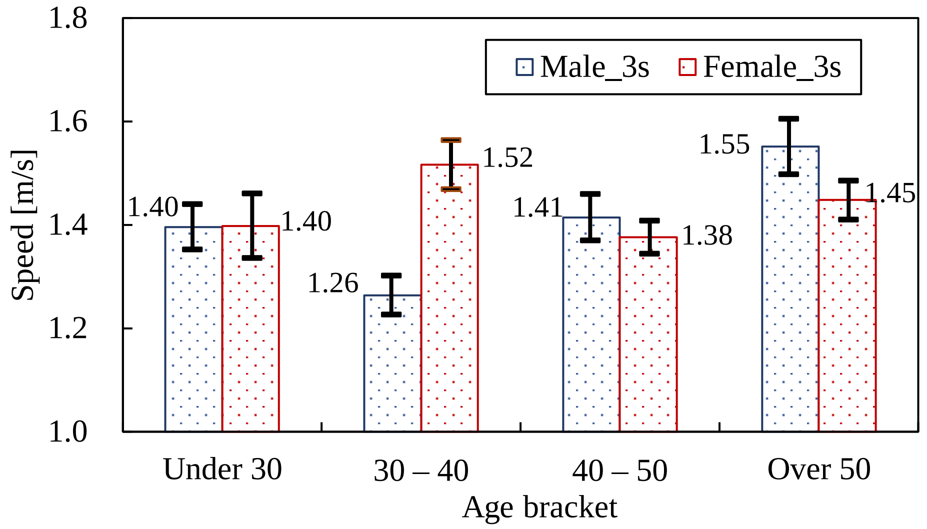


Figure 10 Walking speeds in the no motorbike section(3s)

Regarding the issue of body size, the maximum evacuee density in no motorbike section is around 0.56 person/m^2 (1.78 m^2 per person), compared to the surface for an average pedestrian (0.13–0.17 m^2, see Figure 11) reported by Buchmueller, S., & Weidmann, U. (2006).[44], the space for personal activity is relative enough (the ratio of Individual occupied area and individual's area shown as Figure 11).

When further discussing the motorbike section, the minimum occupied area of a motorbike is around 2.63 m^2/motorbike (corresponding to motorbike density 0.38 motorbikes/m^2), one motorbike's area is around 1.26 m^2 (the ratio of a motorbike occupied area and a motorbike's area shown as Figure 12). The placement of motorbikes does not completely seal off the path.

Moreover, we observed that subjects with relatively large body sizes were obstructed by motorbikes or needed to turn their body to one side to pass through the gap between motorbikes (see Figure 13) after re-check the video recording. But the mean walking speed with different body sizes (shown in Figure 14) has no significant difference be observed. (Note: the medium body size takes the range of 18.5≤ BMI (Body Mass Index) < 24 as a reference.)

Therefore, we consider that even though subjects with relatively large body size might be temporarily obstructed by motorbikes or need to turn their body to one side to pass through the gap between motorbikes, the influence of body size on walking speed is still insignificant compared to the order of start walking and evacuee densities.

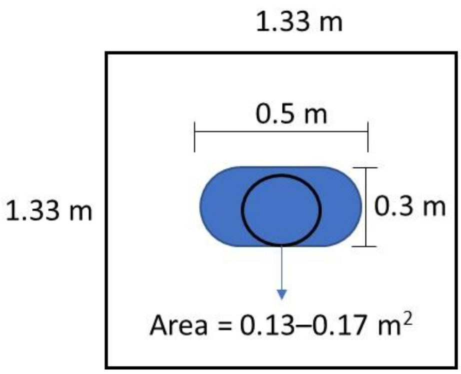


Figure 11 Ratio of Individual occupied area and individual’s area.

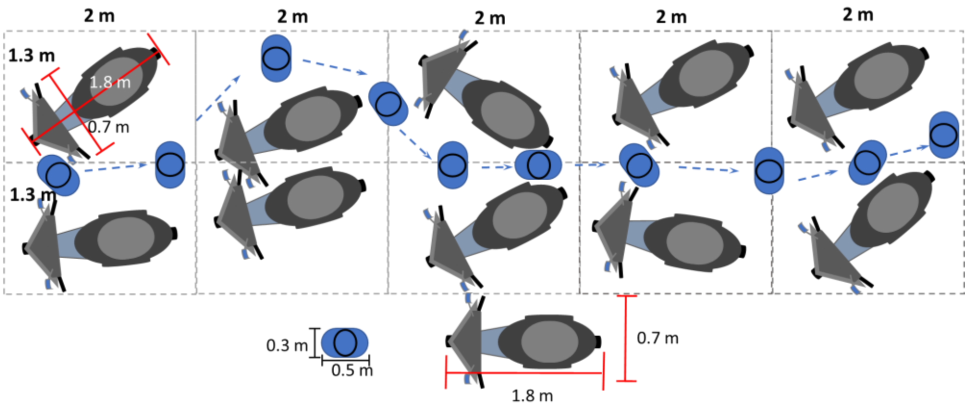


Figure 12 Ratio of a motorbike occupied area and a motorbike's area.

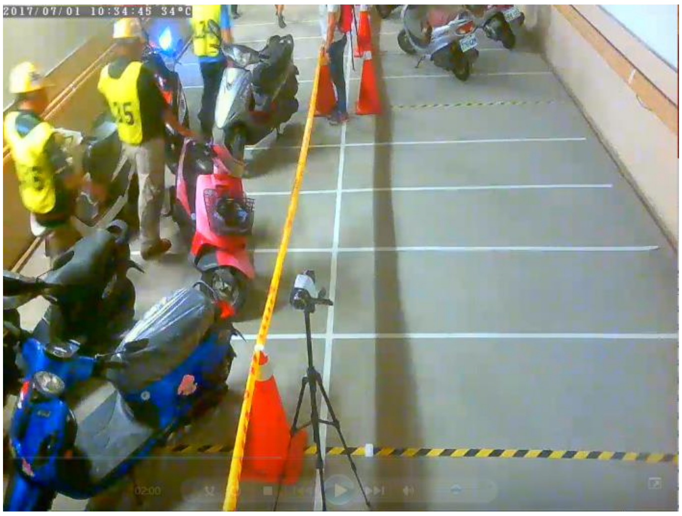


Figure 13 Screenshot of subjects passing motorbike section (motorbike density 0.38 motorbikes/m^2).

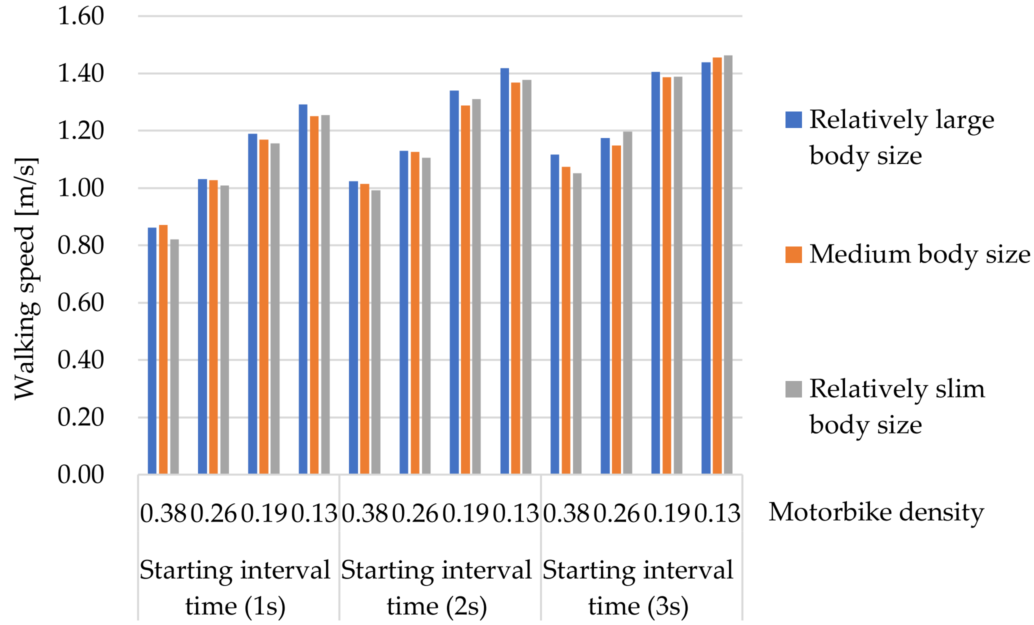


Figure 14 mean walking speed based on the category of body size.

Considering the difference in the motorbike density (0.38, 0.26, 0.19, and 0.13 motorbikes/m^2) and evacuee density, a total of 24 cases were included in the present experiment(Including normal walking speed and emergency evacuation speed scenarios). Table 8 describes the conditions of the experiment cases.

Table 8 Experiment conditions

Scenario	Rounds	Instruction of Starting Interval Time (s)	No-Motorbike Section (m)	Motorbike Section (10 Motorbike Setting Length (m))
Normal walking speed	1	1	10 (front), 30 (rear)	10
	2		15 (front), 20 (rear)	15
	3		10 (front), 20 (rear)	20
	4		15 (front), 5 (rear)	30
	5	2	10 (front), 30 (rear)	10
	6		15 (front), 20 (rear)	15
	7		10 (front), 20 (rear)	20
	8		15 (front), 5 (rear)	30
	9	3	10 (front), 30 (rear)	10
	10		15 (front), 20 (rear)	15
	11		10 (front), 20 (rear)	20

	12		15 (front), 5 (rear)	30
Emergency evacuation speed	1	1	10 (front), 30 (rear)	10
	2		15 (front), 20 (rear)	15
	3		10 (front), 20 (rear)	20
	4		15 (front), 5 (rear)	30
	5	2	10 (front), 30 (rear)	10
	6		15 (front), 20 (rear)	15
	7		10 (front), 20 (rear)	20
	8		15 (front), 5 (rear)	30
	9	3	10 (front), 30 (rear)	10
	10		15 (front), 20 (rear)	15
	11		10 (front), 20 (rear)	20
	12		15 (front), 5 (rear)	30

2.5 Calculation of time intervals in the specific section

Since we hope to investigate the interference between adjacent evacuees on the walking speed and the evacuation speed, we instructed the subject to start walking after the previous subject has walked at around 1 s, 2 s, and 3 s later. Considering the evacuee density means the number of people per unit area and the area can be expressed by the distance between adjacent subjects multiplied by the width. We first calculated the individual time interval ($\Delta t_n^{k,k+1}$) and then calculated the evacuee density of an individual in a specific section based on the individual time interval. Nonetheless, after subjects started to move, there would be mutual influence due to the proximity of the distance, which changed the personal density.

Figure 15 is the time from the initial starting point of case 1 to the arrival of each checkpoint. It can be show from the figure 15 that the time interval between the experimenters starting from the start is 1 second, but with the difference in individual walking time, the time at each checkpoint will be different, and there are even cases where it passing maneuvers.

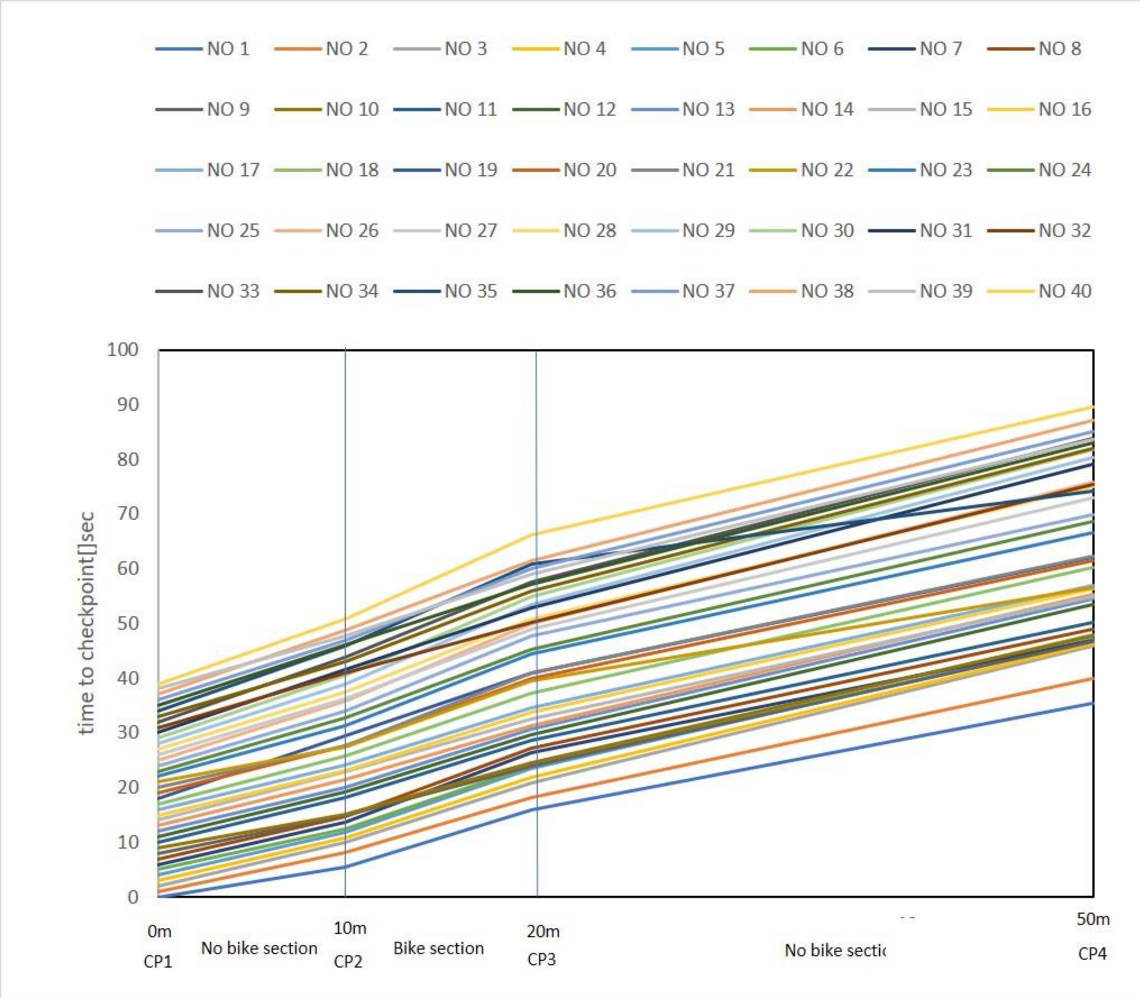


Figure 15 Time from departure to checkpoint (normal walking case 1)

Since we can't specifically grasp the change in the distance between adjacent subjects during the whole walking process, we applied the approach of "time averaging" to estimate the distance between adjacent subjects (i.e., considering the mean time interval while adjacent subjects entered and left the specific section in the motorbike lane.)

Firstly, we calculated the time point (T_n^k) of subjects passing each checkpoint base on the time when 1st subject started walking. The formula can be expressed as Eq 1:

$$T_n^k = (n-1)\Delta T + t_n^k \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 1}$$

where T_n^k denotes the time point when the *n*-th subject passed the checkpoint *k*, and it is relative to the time when 1st subject started walking; *ΔT* denotes the starting interval time = 1s, 2 s, 3 s, t_n^k denotes the time from the *n*-th subject start timing at CP_1 or CP_5 to CP_k (by personal stopwatch); *n* denotes the order of subject start walking, and *n*= 1 to 40; *k* denotes the number of checkpoint (CP) order, and *k* divide as two sections 1 to 4, and 5 to 8.

And then, the time interval of the *n*-th subject is determined by the behavior of the five (including himself) subjects (see Figure. 16). When each subject entered the specific section (CP_k), the time point (T_n^k) would be recorded, and then the time point of the rear subject would also be recorded when he (she) entered the specific section (CP_k) (Shown in Figure 16(1) to Figure 16(2)). Similarly, these adjacent subjects of front and rear would keep walking until leaving the specific section (CP_{k+1}), and the time point (T_n^{k+1})were recorded, respectively (Shown in Figure 16(3) to Figure 16(4)).

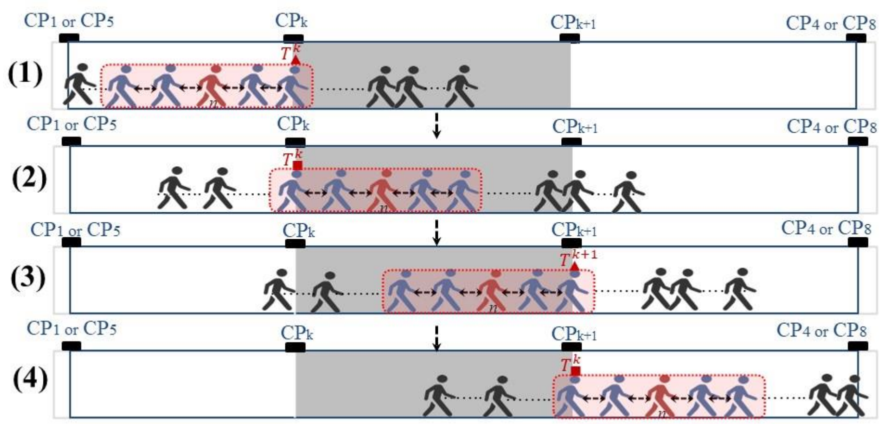


Figure 16 Schematic diagram of average interval time calculation.

However, there have some subjects that would cross the front subjects (i.e., passing maneuvers). At that time, if the calculation is based on the order of starting walking, the time interval would appear negative value, which results in the density would be negative.

Since the present study doesn't further discuss the influence of passing maneuvers, to avoid this peculiar phenomenon causing negative values in the time interval, we considered that a subject's time interval in a specific section was based on the time difference between two-front subject and two-rear subject passing the checkpoint rather than the order of start walking. Thus, we calculated the average time difference of four adjacent subjects nearby a target subject (red humanoid icon in Fig. 16) when he(her) passed the checkpoint. And then define an average of these time differences as the time interval of the target subject. By averaging the time difference of four adjacent subjects around, the calculation error in density caused by passing maneuvers can be mitigated.

The formula for the time interval of the *n*-th subject entering the specific section can be expressed as Eq 2:

$$\Delta t_n^k = \frac{1}{4}\left(T_{\blacksquare}^k - T_{\blacktriangle}^k\right) \qquad \text{Eq 2}$$

Where $T_{\blacktriangle}^k$ denotes the time point of the front-two subject of the target subject (*n*-th subject) passed the checkpoint *k*; $T_{\blacksquare}^k$ denotes the time point of the rear-two subject of the target subject (*n*-th subject) passed the checkpoint *k*. It should be noted here that for the first two and the last-two subjects who entered or left the experiment section, considering there are no subjects or only one subject in front or behind them, the numeric "4" in Eq. (2) would be adjusted as "3" or"2".

And then, the time interval of an individual in the specific section can be expressed as Eq 3:

$$\Delta t_n^{k,k+1} = \frac{1}{2}(\Delta t_n^k + \Delta t_n^{k+1}) \qquad \text{Eq 3}$$

Based on the calculation of personal time interval ($\Delta t_n^{k,k+1}$) in the specific section, the evacuee density (ρ_e) can be expressed as $\rho_e = 1 / (wV\Delta t_n^{k,k+1})$, where w is the width of the specific section; V is the individual's walking speed in the specific section. And $V\Delta t_n^{k,k+1}$ express the distance between adjacent subjects in the x-direction.

2.6 summary

This chapter explains the literature review of Experimental design, the experiment place selection, experimental design, experimental process, and experimental cases. The motorbike flow and density analysis are also carried out for the actual traffic accident cases in the motorbike lane of the Kaohsiung Crossing Harbor Tunnel, and the calculation of the time interval of the specific section of the experiment is explained. The main results are as follows:

1. Considering the issue of experimental traffic control in the motorbike lane of the Kaohsiung Crossing Harbor Tunnel, we chose the underground passageway of Chiayi Chang Gung Memorial Hospital as the experimental site. Furthermore, we considered that the tunnel evacuation may be at a normal walking speed or evacuate by brisk walking or jogging (semi-jogging), we choose two scenarios of normal walking speed and emergency evacuation speed for experiments. On the other hand, two different factors affect the speed of evacuation, one is evacuee density and the other is motorbike density. Therefore, we designed the departure interval time of each experimenter to be 1 second, 2 seconds, and 3 seconds to distinguish different evacuee densities. In addition, we design different motorbike densities to be 0.38, 0.26, 0.19, and 0.13 motorbikes/m^2 to distinguish different motorbike densities. In this way, 24 experimental cases were designed.

2. By observing the walking speed of males and females in the present experiments

can find that the influence of age and gender has the difficulty in clarification. Even appeared as an unnatural situation where females walk faster than males. The reason is unclear, but the results reflect that the influence of the different ages and genders could not be observed in the present experiments. Therefore, the experimental results would only focus on discussing the relationship between walking speed and evacuee density.

3. Regarding the issue of body size, the space for personal activity is relative enough in this experiment, and further discussing the motorbike section, the mean walking speed with different body sizes has no significant difference observed. So the influence of body size on walking speed is insignificant.

4. The motorbike flow rate in a traffic accident (0.12 motorbikes/s) was only around one-third of the flow rate in rush hour. It implies that once the incident occurs in the tunnel during rush hour, there would be adding three times as many motorbike users stranded inside the tunnel, compared to this real traffic accident. Therefore, it can expect that the difficulty in the motorbike lane evacuation would also increase once the fire occurs during rush hour.

5. The analysis of this traffic accident revealed that motorbikes congested the lane, and the motorbike density reached a constant value with limited lane space. This indicates that motorbikes involved in a tunnel accident would result in the accumulated distance of motorbike congestion extending rather than the motorbike

density increasing. This reflects the necessity of timely traffic control for motorbike lanes in an emergency to prevent an increase in tunnel users needing evacuation.

6. Perform regression analysis on the number of motorbikes accumulated at 30-second intervals within 5 minutes after the actual traffic accident in the motorbike lane of the Kaohsiung Crossing Harbor Tunnel and the corresponding distance, and the regression equation of y=0.98x-5.42 can be obtained. 5.42 meters means that the first motorbike stops approximately 5.42 meters from the starting point of the calculation. This result will be an important parameter for future safety assessment of tunnel motorbike lanes.

7. The time interval calculation of a specific section in the experiment has a great relationship with the calculation of the evacuee density. The time interval of each experimenter in a specific section is different from the time interval of departure. Through the study of the calculation method, the calculation of the individual time interval in a specific section can be confirmed, and then the individual evacuation density can be calculated.

3. Influence of evacuee density and motorbike density on normal walking speed

3.1 Influence of evacuee density on normal walking speed

3.1.1 Walking speed in the no-motorbike section and modeling

To model the walking speed considering the evacuees' density, we also analyzed the diagram of the speed-density relationship from the present experimental data of no-motorbike sections and reviewed the literature on the speed-density relationship in pedestrian facilities and buildings (see Fig.17 and Table 2).

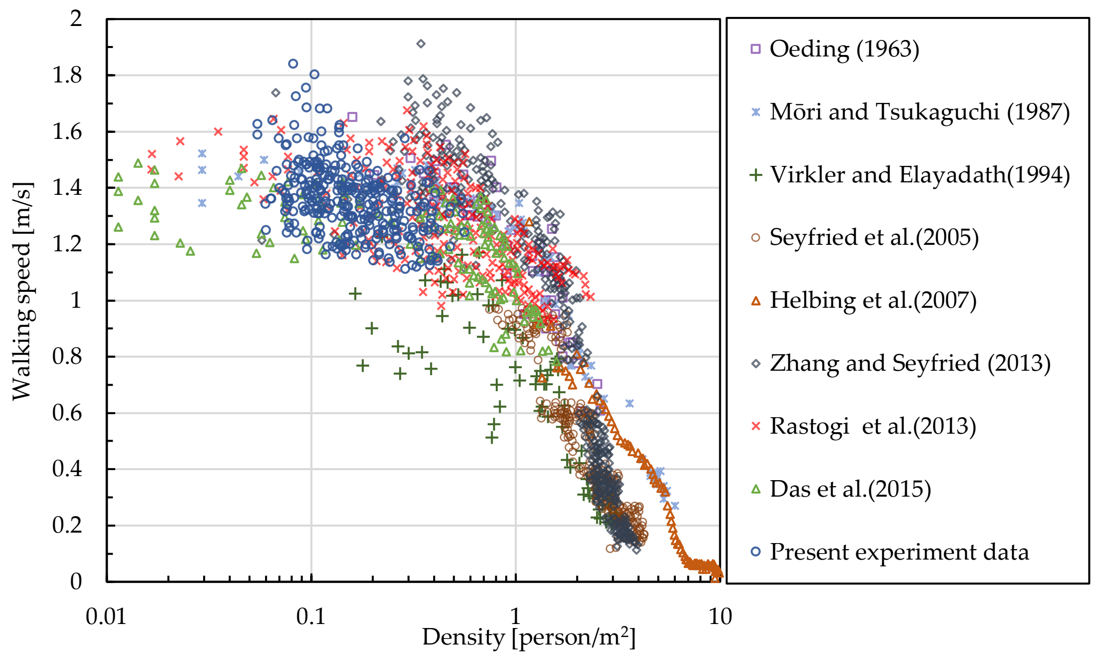


Figure 17 Macroscopic fundamental diagram of speed-density relationship from experiment and observation data.

Based on the review of the experimental or observational literature in Table 2 and Figure 17 can find that the existing studies over a wider range of walking speeds [27–

34]. In addition to the relationship between density and walking speed, Oeding (1963), Mōri and Tsukaguchi (1987), Rastogi et al. (2013), and Das et al. (2015)'s investigation of different pedestrian facilities is based on actual observations, so bi-directional pedestrian movement is considered [27,28,29,33]. Helbing et al. (2007) discuss the extremely high-density condition that was close to crowd panic [34].

The fundamental diagram of the speed-density relationship in Figure 17 reveals the diversity of the findings considering different factors (i.e., various types of infrastructure, the composition of age and nationality, the direction of the human flow, travel purpose, etc.), which vary across the studies. To confirm whether the various research data can be integrated or not, we compared the similarity of the four aspects (i.e., the scenarios, the direction of the human flow, density range, and the geometry of walking space) with other studies (see Table 2). It can be seen from Table 2 that the present study is not similar to other studies in four aspects. The scenario is much focusing on evacuation rather than the investigation of the pedestrian flow in pedestrian facilities. Furthermore, Figure 17 also indicates that the present experiment is significantly different from past studies in the aspect of the density range focused. Considering the similarity is not much fitting, the following walking speed modeling process would be done based on the present experimental data.

On the other hand, regarding the individual walking speed in a road tunnel, an evacuation experiment has conducted in a full-scale tunnel (with ceiling lighting) in 2015. The average age of subjects is 35.1 years old. In the experiments at that time, the walking speed was measured under the condition that subjects start walking at an interval time of more than 30 s (assuming no interference between adjacent evacuees). The scenario assumed a normal situation such as commuting to work or school (a non-urgent evacuation situation). According to the results, the walking speed of an individual was in the range of 0.94–1.88 m/s (mean 1.45 m/s) [43].

Considering subjects in the front no-motorbike section (Section 1 and Section 4) would suddenly speed up and speed down when they started walking and enter the motorbike section (see Fig. 5), the speed does not ensure that steady-state speed was approached before timing began. Since we focus on the walking speed in a steady state rather than suddenly speeding up and speeding down, we consider the front no-motorbike section as a buffer to minimize the effect during entering the lane and choose the data of the rear no-motorbike section (Section 3 and Section 6) to analyze. Moreover, since the present study hopes to clarify the influence of the interference between adjacent people on walking speed in low human density, the first few subjects who start walking is expected that they walk not affected by other since no one is in front, or the distance is relatively long. Thus, we exclude the data of the first five subjects when analyzing the walking speed.

Figure 18 illustrates the walking speed against the $1/\rho_e$ (personal area module). Walking speed ranged from 1.11–1.84 m/s with the personal area module of 1.78–18.31 m^2 (evacuee density: 0.05–0.56 person/m^2). Moreover, walking speed would also slightly decrease with the increase of density even when the personal area module was around 10 m^2 (evacuee density: 0.1 person/m^2). And the tendency seems to decrease exponentially. Therefore, to develop the deterministic model, as the first step, we assume the walking speed (V) is affected by the factor of evacuee density can express in the following form.

$$V = V_0 \ f(\rho_e) = V_0 \ (1 - a e^{\frac{b}{\rho_e}}) \qquad \text{Eq 4}$$

Where $f(\rho_e)$ means a function to quantify the influence of evacuee density on walking speed. V_0 is denoted as a free walking speed that is not affected by the evacuee density in the present study (i.e., the individual's walking speed without being affected by others). a, and b are the parameters that affect the shape of the assumed function.

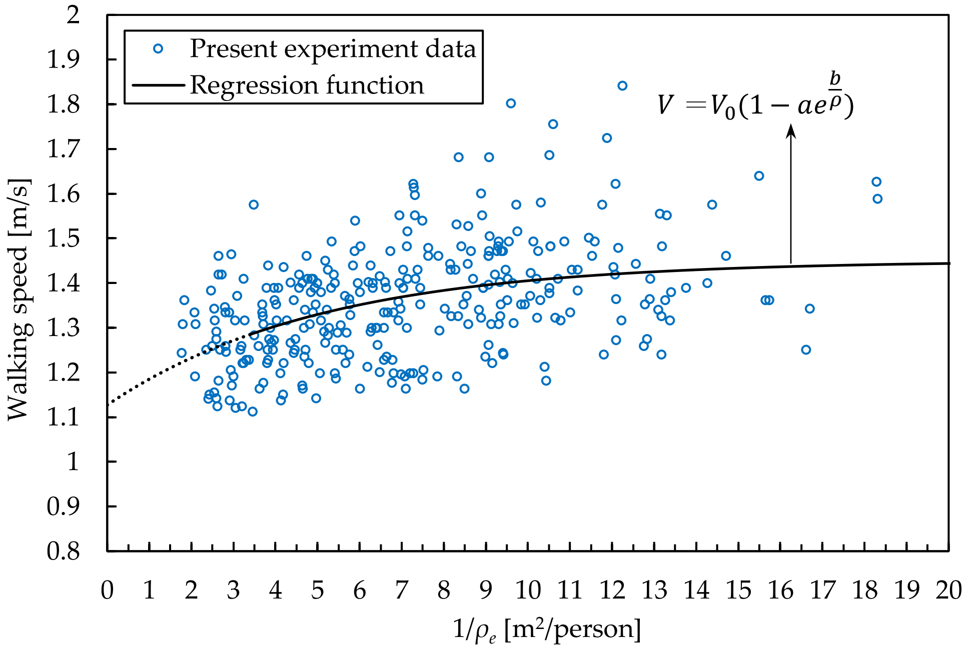


Figure 18 Diagrams of speed and personal area module relationship.

Regarding the V_0, it varies with different travel purposes. The average free walking speed has been reported as 1.34 m/s based on the measurements done in the past [44].

The studies in Japan reported that the average walking speed in the evacuation was around 1.30 m/s –1.33 m/s [45–47]. The walking speed when going to the company to work in the morning was close to 1.50 m/s [48–49]. It was significant that free walking speed should be considered as the stochastic variable with distribution [50] depending on various factors even though the effect of human density has been excluded. However, it is also a reasonable approach to simply describe the free walking speed (V_0) by a mean value. To determine free walking speed (V_0) reasonably, we took the results of normal walking speed in the real tunnel evacuation experiments (Yamashita, 2018) [43] as the reference of V_0, which is higher than the mean value reported by Buchmueller and Weidmann (2006) [44], but still in the range of past research on free walking speed and much close a scenario of evacuation.

The parameters a and b in Eq. (4) are estimated through the non-linear regression by applying the least square method. The regression curve is shown as the black line in Fig. 18, and the regression function is expressed as Eq 5.

$$V = V_0 \ f(\rho_e) = 1.45(1 - 0.22e^{-\frac{0.20}{\rho_e}}) \qquad \text{Eq 5}$$

3.1.2 Two-regime models for walking speed

In this subsection, we keep discussing the modeling process of walking speed. It has been well known that the walking speed should naturally decrease and approach zero when the area occupied by an individual becomes extremely small. However, a further examination of the regression function in Figure 18 and Eq. (5) can find that the regression function in Figure 18 is close to the value of 1.1 m/s when the area occupied by an individual becomes small. This tendency is different from actual crowd characteristics. It could be considered that the regression function Eq. (5) cannot explain the region where the evacuee density is higher than the experimental range. Therefore, to connect a model that can be used for walking speed at low density and high density, we further considered that the relationship between walking speed and evacuee density can be described by the two-regime models and assumed another exponential function for describing walking speed in the high-density state as Eq 6.

$$V = c[e^{-\rho_e d} - e^{-5.4d}] \quad \rho_i < \rho_e \leq 5.4 \qquad \text{Eq. 6}$$

Where c and d are the parameters that affect the shape of the assumed function; 5.4 person/m^2 is the maximum admissible density corresponding to null speed (speed close to 0 m/s) which is based on the reference of Weidmann (1993) [51]; ρ_i means the dividing condition for Eq. (5) and Eq. (6). If ρ_i is determined, the shape parameters c and d can be determined by both following conditions.

(1)The same walking speed between Eq. (5) and (6) in the condition of density ρ_i.

(2)The same slope condition between Eq. (5) and Eq. (6).

In this paper, ρ_i is determined by trial and error at 0.3 person/m^2. The calculated function is expressed by the following function Eq 7.

$$V = 2.42[e^{-0.16\rho_e} - e^{-0.86}] \qquad 0.3 < \rho_e \leq 5.4 \qquad \text{Eq. 7}$$

Figure 19 illustrates the scatter plot of the walking speed against evacuee density of the no-motorbike section and the speed-density models proposed by Rastogi et al. (2013)

[27], Das et al. (2015) [29], and Kladek (1966) [38]. To present the low-density data distribution more clearly, the *x*-axis is expressed in logarithmic coordinates in Fig.19.

Rastogi et al. (2013)'s model [27] was revisited from Underwood Model (1961) [37] based on the original data from different pedestrian facilities. Das et al. (2015) 's model [29] was revisited from the Greenshields' Model (1935) [35]and Underwood Model (1961) [37] based on the original data from sidewalks and carriageways around transport terminals (only the model revisited by the sidewalk data shown in Figure 19). Kladek (1966) [38] proposed a single formula to describe the relation between speed and density of urban road traffic. And Weidmann (1993) [51] further revisited the formula to express the natural human movement characteristics at high and low densities as Eq 8:

$$V = 1.34\left\{1 - e^{\left[-1.913\left(\frac{1}{\rho e} - \frac{1}{5.4}\right)\right]}\right\} \qquad \text{Eq. 8}$$

Where 1.34 [m/s] means the free walking speed; -1.913 is the parameter that affects the shape of the Kladek formula; 5.4 person/m^2 is the maximum admissible density corresponding to null speed [38,51].

Rastogi et al. (2013) [27] and Das et al. (2015)'s model [29] in Figure 19 reveals that walking speed decreased with the density increase, even when the density is extremely low. However, in general, if an individual keeps a certain personal space, he (or she) can walk freely without being affected by others [48–49]. Therefore, it should be considered that in a state of extremely low density, the walking speed is independent of the influence of densities. Thus, the proposed model from Rastogi et al. (2013) [27] and Das et al. (2015) [29] may be unrealistic in the low-density state. On the other hand, the Kladek formula [38,51] in Figure 19 reveals that the walking speed began to decrease when the density was around 0.4 person/m^2. This prediction overestimates the density condition when walking speed begins to decrease, compared to our experimental results. Relatively, the proposed two-regime models (light and dark blue lines) appear in good agreement with the current experimental data.

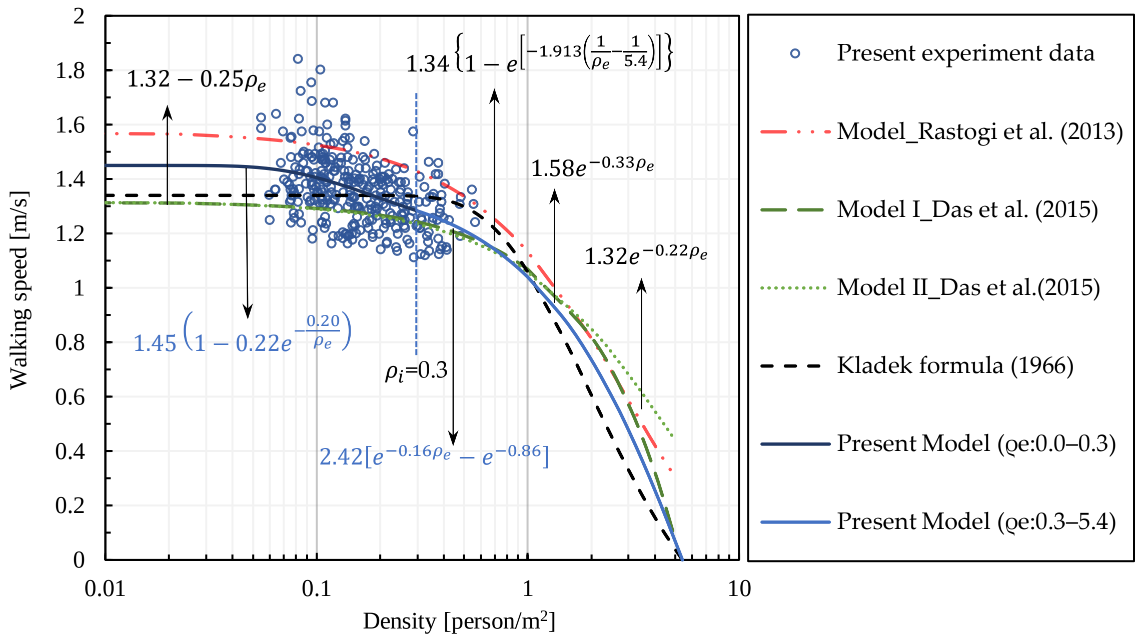


Figure 19 Speed-density relationship and modeling function.

Furthermore, to further verify the two-regime models, the root-mean-square error (RMSE) of the model proposed by other studies and present models is shown in Table 7.

The function of RMSE is expressed as Eq 9:

$$RMSE = \sqrt{\frac{\sum_{i=0}^{n}(V_i-\hat{V}_i)^2}{n}} \qquad \text{Eq. 9}$$

Where V_i means the experimental data from the present study; $\hat{V}_i$ means the estimated value from the models; n means the sample number.

According to Table 9, the proposed two-regime models have minimum RMSE compared to other models, indicating good fitness.

Table 9 RMSE between walking speed data and fitting model.

Model	**Rastogi et al. (2013) [27]**	**Das et al. (2015) (Model I) [29]**	**Das et al. (2015) (Model II) [29]**	**Kladek formula (1966) [38,51]**	**The present study (Two-regime models)**
RMSE	0.174	0.146	0.148	0.127	0.113

3.1.3 Discussion on Quadratic Differentiation of Low-Density Equation

In the course of the study, we will assume that equation (4) is because it has the property that the calculated velocity (V) is not affected when the density (ρ) is extremely low. This characteristic is in line with the characteristic that the speed of a person will not theoretically decrease due to changes in density when the surrounding space is infinite.

Considering the directions that can be explained by the mathematical calculation process, a reasonable point of inflection can be obtained at ρi=0.2 through the quadratic differentiation of equations (5) and (6). But the derived problem is that equation (5) proposed in this study is a prediction equation based on experimental data, but equation (6) is an equation based on previous research data. If the connection point is selected at the point of inflection, although it can be explained in the process of mathematical calculation, it will reduce the meaning of equation (5) proposed in this study. In addition, if the proposed connection point is assumed to be 0.2 (ρ_i=0.2), the RMSE calculated in the whole equations (5) and (6) is 0.14, the error of the RMSE increases instead, and will exceed the Kladek formula (1966) RMSE (0.127).

Another more intuitive angle to explain why ρ_i=0.3（$1/\rho_i$=3.3) is chosen, which will be closer to the limit value of the experimental data. Therefore, the purpose statement is that ρ_i=0.3 is a more reasonable value considering the area covered by the limit value of this experiment, that is, equation (5) can cover most of the experimental data as much as possible. Although the point of inflection will still appear in the range of Equation (5), it will cover less experimental data.

In fact, the purpose of the present research is to show that when the experimental data has low density, the velocity will show a slight downward trend. Because of this, we will consider that equation (5) can cover as much experimental data as possible, and consider the decrease of the velocity curve with the change of density (ρ) to maintain a smooth state as much as possible, and reduce too much deviation from other empirical curves that explain the relationship between velocity and density. Although the ρ_i=0.3 we mentioned as the connection point cannot satisfy both the explanation of the relationship between velocity and density, as well as the explanation of the meaning of mathematical calculation, it should be a more suitable explanation for the present study.

3.2 Influence of motorbike density on normal walking speed

3.2.1 Walking speed in the motorbike section and modeling

In this section, we further clarify the influence of motorbike density on walking speed and discuss the modeling process. As demonstrated in Figure 5, there were 10 motorbikes set up in the motorbike section (see the red section in Figure 5). The section lengths (L) with motorbikes were set up as 10 m, 15 m, 20 m, and 30 m depending on experiment cases. Considering the width (w) of the motorbike lane, the motorbike density (ρ_b) can express as $\rho_b = N / (wL)$.

Moreover, the function $V = V_0\, f(\rho_e)$ in Section 3.1 can further consider the influence of motorbike density and be rewritten in the following form, as Eq 10.

$$V = V_0 \ f(\rho_e) g(\rho_b) \qquad \text{Eq. 10}$$

Where, the function of $g(\rho_b)$ is assumed to represent the influence of motorbike density, and it can also rewrite as $V/ (V_0\, f(\rho e))$. Since the $f(\rho_e)$ has been calculated in sections 3.1.1 and 3.1.2, and the evacuee density in the motorbike section is around 0.06 – 0.79 person/m^2, we can further apply Eq. (5) and Eq. (7) to Eq. (10). In addition, to establish a criterion of walking speed that is not affected by "motorbike density (ρ_b)", we also consider the V_0 as the average walking speed (1.45 m/s) that is mentioned in Section 3.1. The result of function $g(\rho_b)$ against the reciprocal of ρ_b is shown in Fig. 20.

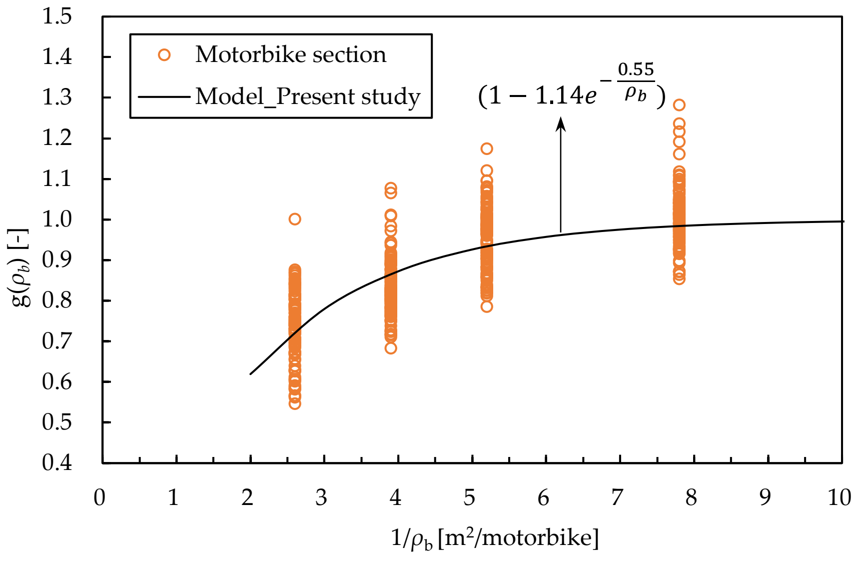


Figure 20 Relationship between g(ρb) and motorbike density (ρb).

Figure 20 indicates that $g(\rho_b)$ was mainly divided into four groups as the four motorbike densities were considered in experiments. Moreover, the distribution of data points in Figure 20 reveals that $g(\rho_b)$ gradually decreased with the increase of motorbike density (i.e., $1/\rho_b$ decreased), and the tendency seemed to show an exponential relationship. Thus, we further assumed the function $g(\rho_b)$ is the same as the form of Eq. (4) and conducted the non-linear regression by applying the least square method to estimate parameters in the function $g(\rho_b)$. The regression curve is shown as the black line in Figure 20, and the regression function is generated as Eq11:

$$g(\rho_b) = (1 - 1.14e^{-\frac{0.55}{\rho_b}}) \qquad \text{Eq. 11}$$

Apparently, the regression function is well-fitted with the mean of function $g(\rho_b)$ in each motorbike density. But in the same motorbike density, the difference in individual walking speed still exists.

Moreover, it should be noted that we mainly focused on actual motorbike density in an accident and the relatively lower density than an actual accident, based on the accident investigation mentioned in Section 2.3. However, when a tunnel fire accident occurs, an extreme situation is that motorbikes are probably congested in the lane so that people can't walk in the motorbike lane, but such motorbike density conditions have not been explored in the present experiments. Whether the current regression function can explain the walking speed under the condition of high motorbike density is unclear. Therefore, the regression function in Fig. 20 was only expressed until the reciprocal of ρ_b is 2 (i.e., the motorbike density is equal to 0.50 motorbike /m^2).

3.2.2 Motorbike lane evacuation models and limitations

Since Figure 19 and Figure 20 reveal the relationship between walking speed, evacuee densities, and motorbike densities, the function for modeling motorbike lane evacuation considering both the evacuee density and motorbike density can be presented as the following functions Eq 12 and Eq13:

$$V = V_0\left(1 - 0.22e^{-\frac{0.20}{\rho_e}}\right)\left(1 - 1.14e^{-\frac{0.55}{\rho_b}}\right) \qquad 0 < \rho_e \leq 0.3 \qquad \text{Eq. 12}$$

$$V = V_0\{1.67[e^{-0.16\rho_e} - e^{-0.86}]\}\left(1 - 1.14e^{-\frac{0.55}{\rho_b}}\right) \qquad 0.3 < \rho_e \leq 5.4 \qquad \text{Eq. 13}$$

To verify the models of walking speed, we applied Eq. (12) and Eq. (13) to estimate the walking speed and compared the measured walking speed in the present experiments. The V_0 is assumed to the 1.45 m/s. Each modeled walking speed is calculated based on the same condition of evacuee density and motorbike density from the measured walking speed. The modeled walking speed is shown on the *y*-axis and the measured walking speed is shown on the *x*-axis in Figure 21.

The result reveals that the slope of linear regression in Figure 21 is 0.98, and R-squared (R^2) is 0.99. Modeled walking speeds are in acceptable agreement with the walking speed in experiments. Therefore, the regression models which consider variables of evacuee density and motorbike density can be an approach to reproducing the walking speed in motorbike lane evacuation in the tunnel.

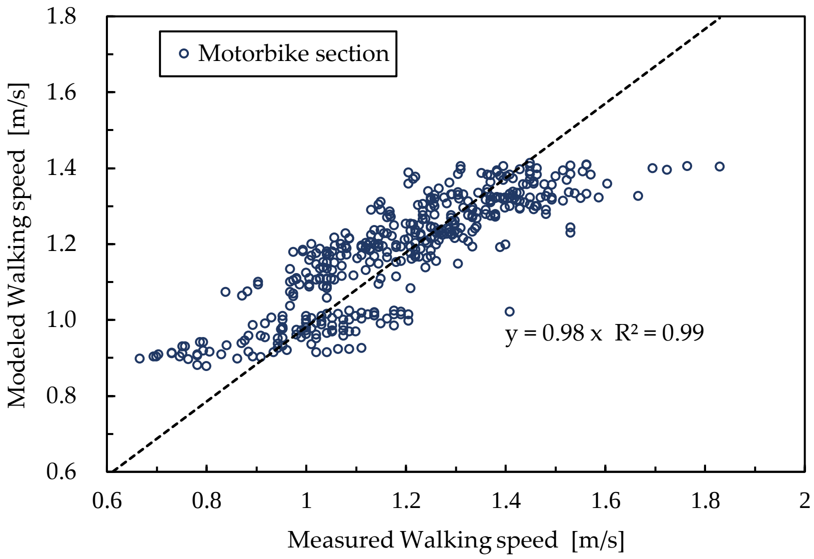


Figure 21 Measured walking speed and modeled walking speed.

However, there are some limitations to the development of the model that needs to be noted. The focus of the present study was on developing models that can explain the relationship between walking speed, evacuee density, and motorbike density in the motorbike lane in the tunnel. From the composition of the model can find that the prediction of free walking speed (V_0) would greatly affect the reproducibility of the model. Moreover, the proposed model in the present study should be served as a deterministic model that is based on the experimental data and past literature to determine the necessary parameters of the model. In particular, the variation of density in this study mainly depends on the designed "starting interval time" of 1 to 3 s, which causes the density range of the experiments to be concentrated in a relatively limited interval. The estimation of the parameters in the model should also be adjusted or revised when more samples from the experiments or observations were included. Nevertheless, the proposed evacuation model in this study could still be regarded as a preliminary approach to explaining the evacuation behavior of motorbike lanes.

Furthermore, we considered a heterogeneous composition of subjects in the present experiments (i.e., mixed with different gender, and age brackets). Further investigation on the influence of gender and age brackets on walking speed in the motorbike lane has not been clarified even though it is well known that physical ability is different between male, female, and age brackets. Regarding the factor of motorbike density, the walking speed in the condition of motorbike density larger than 0.38 motorbikes/m^2 has not been fully investigated through the present experiments. The evacuation models of motorbike lane walking speed would be more comprehensive by further investigation of various population categories(including body size) and motorbike densities.

3.3 Summary

In the research of this chapter, we use the least squares method to analyze the relationship between normal walking speed and density in the non-motorbike section and motorbike section of the experimental site and establish a model. And the limitations of the experiment are explained. The main results are as follows:

1. We analyze the experimental data of the non-motorbike sections in the experiment, and use the least squares method to propose a curve relationship between evacuee density and speed. Because the experimental data are in the low-density range, we use two-regime models to connect the curves between low-density and high-density. The results show that the curve of the relationship between density and speed and the model equation can reasonably explain the trend that the speed of non-motorbike sections in the tunnel motorbike lane decreases with the increase of density.

2. To further verify the two-regime model, the root mean square error (RMSE) of models proposed by other studies was compared with present models. Compared with other models, the two-regime model proposed in this study has the smallest RMSE, indicating good fitness.

3. In the experimental motorbike section, we also use the least squares method to analyze the curve between motorbike density and normal walking speed; and

propose a modeled exponential equation. This equation can also reasonably explain the trend that the normal walking speed of the motorbike section in the motorbike lane of the road tunnel decreases with increasing motorbike density.

4. This chapter reveals the relationship between walking speed, evacuee densities, and motorbike densities, the function for modeling motorbike lane evacuation considering both the evacuee density and motorbike density; and using a two-regime model to combine low and high evacuee densities. The regression models which consider variables of evacuee density and motorbike density can be an approach to reproducing the walking speed in motorbike lane evacuation in the tunnel.

5. Some limitations of the experiment are also proposed in the present study, including the population density of the experiment is mostly concentrated in the low-density range. In addition, the motorbike density range is not greater than 0.38 motorbikes/m^2. No further surveys were made on population categories(including body size). In the future, the above experimental limitations will be further investigated, and the evacuation model for normal walking speed in the tunnel motorbike lane will be more comprehensive.

4. Influence of evacuee density and motorbike density on evacuation speed

Ensuring rapid evacuation in the tunnel is the most concerning issue of the tunnel management authority. Therefore, we also made 12 experimental cases in the experimental design in Chapter 2. Our study focused on reproducing evacuation velocities relatively close to the maximum value, which represents an important parameter for understanding evacuation behavior.

To investigate the characteristics of the evacuation speed of motorbike users in the tunnel, we also considered two factors that may have influenced the evacuation speed of the subjects in the present study. One is the density of motorcycles and the other is the density of evacuees. The detailed information about these two factors has been explained in Chapter 2, and will not be repeated in this chapter. The effects of evacuee density and motorcycle density on evacuation speed are discussed next section.

4.1 Influence of evacuee density on evacuation speed

4.1.1 Evacuation speed in no-motorbike section

A total of 900 evacuation speed data were collected except for the data in the case of no motorbike section 5 m because the evacuation speed might exist a large error in a such short distance. The average evacuation speeds and 95% confidence interval (95% CI) of the mean value are shown in Figure 22. The descriptive statistics (mean, minimum, maximum, standard deviation, 95% confidence interval) of evacuation speed in the no-motorbike section is shown in Table 10. We classified the evacuation speed data with the evacuee density interval of 0.05 person/m^2 (i.e., 0.00–0.05 person/m^2, 0.05–0.10 person/m^2, …).

The mean evacuation speed is around 1.42–2.05 m/s in different evacuee density ranges. The mean value and 95% CI (Upper and Lower) in the evacuee density range of 0.0–0.05 person/m^2 are 2.05, 2.28, and 1.82 m/s respectively, which is significantly different from the speed (1.34 m/s) in normal walking conditions (Buchmueller, S., & Weidmann, U. 2006)[44]. But close to the average evacuation speed in the case of no smoke in experimental investigations conducted by Seike et al. (2021) [17] and the experiment results conducted by Boer (2002) [52].

Most of the data are in the evacuee density range of 0.05–0.3 person/m^2, and no data in the evacuee density range of 0.55–0.8 person/m^2. The mean evacuation speed, 95% CI (Upper and Lower) in each evacuee density range slightly decreases with the density increase, but the tendency becomes insignificant when evacuee density is over 0.3 person/m^2. This is possibly due to the sample number being reduced to dozens or several in evacuee density over 0.3 person/m^2, which causes the mean evacuation speed to be governed by the few subjects. The reliability of the data over 0.3 person/m^2 is also reduced as a result.

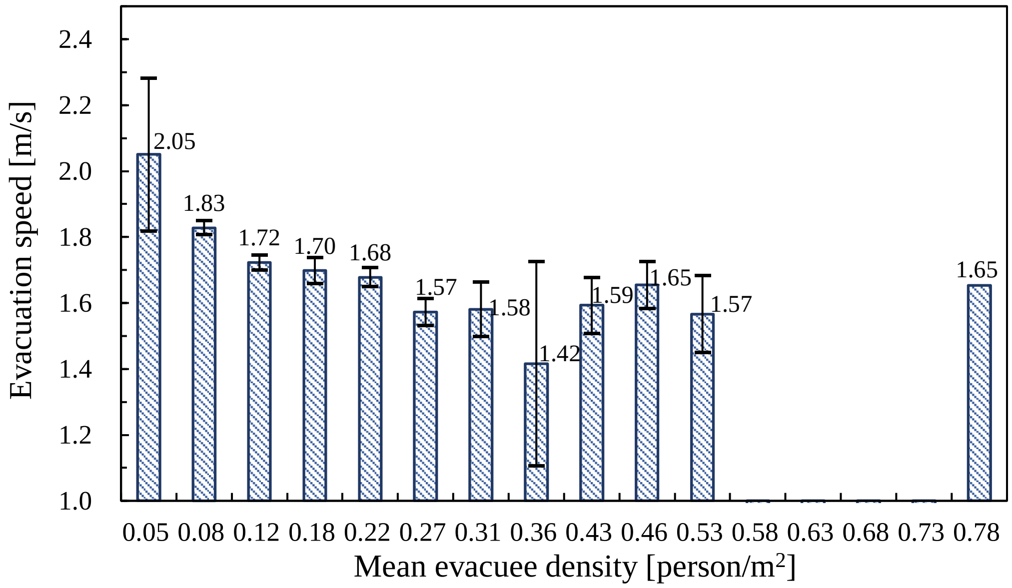


Figure 22 Mean evacuation speed at 0.05 person/m2 range of evacuee density.

Table 10 Descriptive statistics of evacuation speed in no-motorbike section

Density [person/m^2]	# Sample	Mean [m/s]	Max [m/s]	Min [m/s]	Stddev [m/s]	95%CI (Upper) [m/s]	95%CI (Lower) [m/s]
0.0–0.05	6	2.05	2.52	1.77	0.28	2.28	1.82
0.05–0.1	355	1.83	2.50	1.14	0.20	1.85	1.81
0.1–0.15	224	1.72	2.21	0.88	0.17	1.75	1.70
0.15–0.2	96	1.70	2.13	1.12	0.19	1.74	1.66
0.2–0.25	124	1.68	2.02	1.14	0.16	1.71	1.65
0.25–0.3	57	1.57	1.88	1.23	0.15	1.61	1.53
0.3–0.35	17	1.58	1.87	1.35	0.17	1.66	1.50
0.35–0.4	2	1.42	1.57	1.26	0.22	1.73	1.11
0.4–0.45	10	1.59	1.85	1.43	0.13	1.68	1.51
0.45–0.5	3	1.65	1.71	1.59	0.06	1.73	1.58
0.5–0.55	5	1.57	1.75	1.39	0.13	1.68	1.45
0.55–0.6	0	–	–	–	–	–	–
0.6–0.65	0	–	–	–	–	–	–
0.65–0.7	0	–	–	–	–	–	–
0.7–0.75	0	–	–	–	–	–	–
0.75–0.8	0	–	–	–	–	–	–
0.8–0.85	1	1.65	1.65	1.65	–	–	–

The microscopic analysis of pedestrian movement in a normal situation (without push or panic) in a circular passageway conducted by Liu et al. (2009) [53] indicated that the detailed cause of the speed decrease with the density increase is the increase of oscillation amplitude widens the occupation area of people and making the moving efficiency even worse. This viewpoint is based on the observation of actual behavior rather than the discussion of the aspect of cognitive (i.e., how people respond to the movement of other people in the front and adjust their speed and position accordingly). But it still reveals the existence of interference between adjacent people.

The detailed mechanism regarding the relationship between speed and density is complicated because it involves interference derive from physiological and psychological factors, especially the psychological factor that might be variant due to the scenarios (i.e., commuter, evacuation, shopping, etc.) or personal awareness.

Despite this, an accepted concept is that influence of the interference between adjacent subjects would be more significant as density increases, and it would further cause the reduction in evacuation speed. The interesting finding in the present result is that evacuation speed decreases with the density in the significantly lower range still can be observed after moderately excluding the influence of individual variation through the average process.

4.1.2 Evacuation speed modeling by considering evacuee densities

To further modeling the evacuation speed in motorbike lanes, as the first step, we assumed the evacuation speed (*V*) is affected by the factor of evacuee density could express as the form of $V= V_0\, f\,(\rho_e)$. Where $f(\rho_e)$ means a function to quantify the influence of evacuee density on evacuation speed. V_0 is denoted as a free speed that is not affected by the evacuee density in the present study (i.e., the individual's speed without being affected by others).

In the pedestrian flow field, linear [35], logarithmic [36], exponential[37,38,39], and multi-regime models[30] have been applied in describing the speed-density relationship. Considering the adopted models of the speed-density relationship in the pedestrian flow field, we chose the function with an exponential function for modeling in the present study. Regarding the function with exponential relationship, the Kladek formula [38] has been applied to describing the pedestrian flow[44] and the earthquake[54] evacuation because of its continuity and conformity to natural human movement characteristics at high and low densities, so it's suitable for practical use. The model is expressed as Eq. 14:

$$V = V_0 \left[1 - e^{\gamma\left(\frac{1}{\rho_e} - \frac{1}{\rho_{max}}\right)}\right] \qquad \text{Eq. 14}$$

Where V_0, means the free speed; γ is the parameter that affects the shape of Kladek formula; $\rho_{\max}$ implies the maximum admissible density corresponding to zero speed. Regarding the $\rho_{\max}$, the pedestrian's density over 5 person/m^2 is considered hardly move[44,26]. Weidmann,1993[51] further revisits the Kladek formula by considering a maximum density of 5.40 person/m^2 and a free walking speed of 1.34 m/s for pedestrian speed-density relation modeling. Since we have no further data on evacuee density lager than 0.90 person/m^2, the issue about maximum admissible density is not considered in the modeling process in the present study. The assumed function $V = V_0 f(\rho_e)$ is further rewritten as Eq. 15

$$V = V_0 \left[1 - a e^{\frac{b}{\rho_e}}\right] \qquad \text{Eq. 15}$$

Where V_0, is denoted as the free speed in an emergency evacuation situation, a and b are parameters that affect the shape of the regression curve. We used a total of 900 evacuation speed data for estimating the parameters a and b of the function through the non-linear regression by applying the least square method. Regarding the parameter V_0, the research on building evacuation ever pointed out that if an individual keeps a certain personal space, he(her) can walk freely without being affected by others[25,26], and the speed at this time is mainly related to the personal characteristics (age, gender, physical abilities), characteristics of walking infrastructure (length, width, type of pedestrian facility), and other situational factors (such as the purpose for the walk). Thus, it is expected that theV_0 would be the stochastic variable with distribution[50] or simply be described by a mean value[44]. In present study, we took evacuation speed of individual in a road tunnel (human density close to zero) from Boer (2002) [52] and Seike et al. (2021) [17] as the reference.

Boer (2002) [52] conducted experiments to investigate drivers' evacuation activity using a full-scale tunnel in 2001. In experiments, the scenario assumed that there is a tanker on fire. Participants were instructed that they must save their own lives by leaving their vehicles because of the presence of toxic gas and the danger of an explosion. And their evacuation speed was measured by independent observers. The age of the participants was between 20 and 70 years old (average age=42-year-old). In Boer's experiments, evacuation speeds from vehicle to emergency exit were reported as mean 2.20 and 2.30 m/s. The highest speed was 3.1 m/s, and the lowest speed was 1.10 m/s. And observed that 7 participants' speeds varied from snail's pace (0.40 m/s) to running (2.80 m/s).

Seike et al. (2021) [17] conducted experiments in the horseshoe-shaped tunnel with 488-m long, 6.6-m wide, and 5.4-m high in 2015 to investigate the evacuation speed in the condition with and without smoke. The average age of subjects was 41.3-year-old in the case of no smoke. In the experiment, the speed was measured under the condition that subjects start acting at an interval time of more than 30 s by considering the situation without interference between subjects. The scenario assumed an emergency evacuation situation, such as an evacuation broadcast has been done and informed people to evacuate in a hurry. According to the results, the evacuation speed of an individual was in the range of 0.57 to 4.17 m/s (mean=2.03 m/s).

It is evident that in the case of evacuee density range of 0.0–0.05 person/m^2, the present study has a good agreement in both experiment results of Boer (2002) [52] and Seike et al. (2021) [17]. Thus, we considered these two studies as a reference and determined the V_0 as 2.20 m/s to further conduct the non-linear regression process in Fig 23. The regression result is expressed as Eq. 16.

$$V = V_0 \ f(\rho_e) = 2.20(1 - 0.32e^{-\frac{0.05}{\rho_e}}) \qquad \text{Eq. 16}$$

Moreover, Fig. 23 also illustrates the mean, minimum, and maximum evacuation speed of individuals in a road tunnel (human density close to zero) from Boer (2002) [51] and Seike et al. (2021) [17]. As shown in Fig. 23, the curve of the regression function illustrates a similar tendency with present experimental data that evacuation speed distribution slightly decreased with the increase of density (i.e., $1/\rho_e$ decrease) from the evacuee density. But it should be noted that the sample number in the evacuee density range of 0.0–0.05 person/m^2 ($1/\rho_e$ = 20–∞ m^2/ person) and 0.55–0.85 person/m^2 ($1/\rho_e$ = 1.82–1.18 m^2/ person) are relatively few so that might cause partial distortion of nonlinear regression, the evacuation speed estimation in these density ranges need to be explained carefully. Comparing the present experiments with Seike et al. (2021) [17] and Boer (2002) [52]'s results, emergency evacuation speed with lower evacuee density is much close to the mean value of Seike et al. (2021) and Boer (2002)'s results, but relatively close to the minimum value when $1/\rho_e$ increase. It is evident that the influence of evacuee densities on evacuation speed could also be observed even if in the low-evacuee density condition.

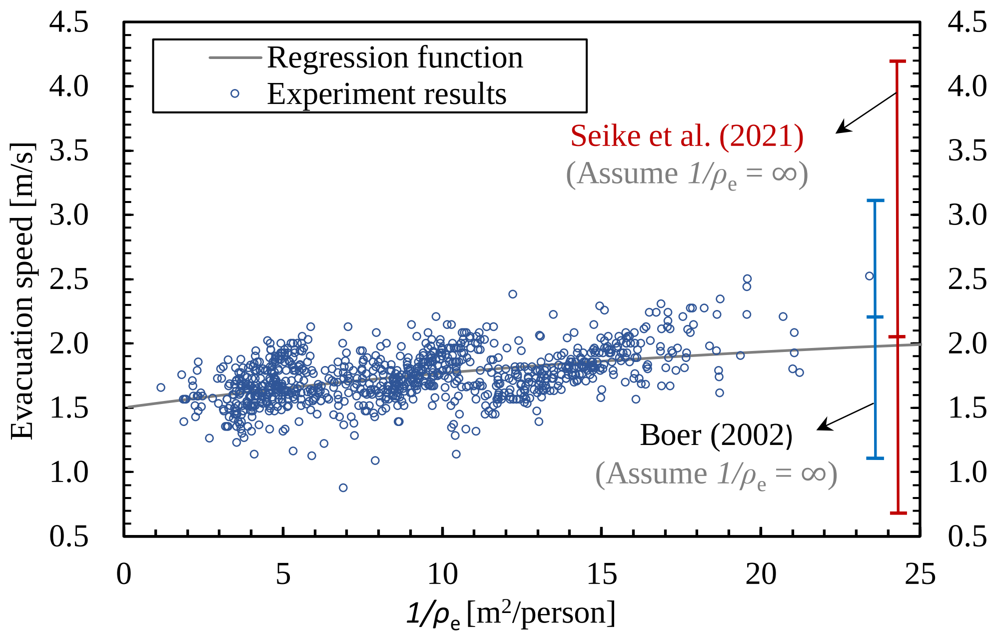


Figure 23 Speed distribution in the no-motorbike section and modeling function

Furthermore, to further verify the present regression function, the root-mean-square error (RMSE) of the model proposed by other studies and regression function is shown in Table 11. The formula of RMSE is the same as in section 3.1.2 Eq. 9 expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=0}^{n}(V_i - \hat{V}_i)^2}{n}} \qquad \text{Eq. 9}$$

Where V_i means the experimental data from the present study; $\hat{V}_i$ means the estimated value from the models; *n* means the sample number (n=900). The parameters of other models were estimated by the mean values in each evacuee density in the present experimental results. According to Table 11, the proposed models have minimum RMSE compared to other models, indicating good fitness.

Table 11 RMSE between the present evacuation speed data and fitting models

Function	Parameters estimation	RMSE

Kladek Model (1966) [38]	$V = V_0 \left[1 - e^{\gamma\left(\frac{1}{\rho_e} - \frac{1}{\rho_{max}}\right)}\right]$	V_0= 1.78 γ= -0.71 ρ_{max}=5.40	0.337
Greenshields's Model (1935) [35]	$V = V_0(1 - a\rho_e)$	V_0=1.88 a=0.42	0.186
Underwood Model (1961) [37]	$V = V_0\ e^{a\rho_e}$	V_0= 1.89 a= -0.58	0.183
Drake's Model (1967) [39]	$V = V_0\ e^{-\frac{1}{2}(a\rho_e)^2}$	V_0= 1.79 a= -1.45	0.191
Present Model	$V = V_0\ (1 - ae^{\frac{b}{\rho_e}})$	V_0= 2.20 a= 0.32 b= -0.05	0.177

4.2 Influence of motorbike densities on emergency evacuation speeds

4.2.1 Evacuation speed in motorbike sections

The descriptive statistics (mean, minimum, maximum, standard deviation, 95% confidence interval) of evacuation speed in motorbike section is shown in as Table 12.

Table 12 Descriptive statistics of evacuation speed in motorbike section

Density [Motorbike/m^2]	# Sample	Mean [m/s]	Max [m/s]	Min [m/s]	Stddev [m/s]	95%CI (Upper) [m/s]	95%CI (Lower) [m/s]
0.38	120	1.35	2.04	0.97	0.19	1.38	1.31
0.26	120	1.48	2.54	0.99	0.22	1.52	1.44
0.19	120	1.65	2.15	1.25	0.18	1.69	1.62
0.13	120	1.74	2.22	1.43	0.17	1.77	1.71

The mean evacuation speed is in the range of 1.35 –1.74 m/s. Compared to mean evacuation speed in the no-motorbike section, mean evacuation speed in four motorbike conditions are lower than the mean evacuation speed in the evacuee density range of 0 –0.1 person/m^2. When the motorbike density in increase to 0.38 motorbike /m^2, the evacuation speed would be much close to the mean pedestrian walking speed (1.34 m/s) in normal condition (Weidmann,1993). This reflects that is indeed impossible to ignore the influence of motorbikes on evacuation speed.

Moreover, the mean evacuation speed and 95% CI (Upper and Lower) slightly decrease with the motorbike density increase. However, it should be noted that in addition to the obstruction of motorbikes, the decrease in evacuation speed also includes the possibility of mutual interference in individuals because motorbikes occupy the walking space and thus bring people closer together.

4.2.2 Evacuation speed modeling by considering motorbike density

Since the influence of evacuee density has been discussed in Section 4.1, this section; would further discuss the influence of motorbike density on evacuation speed in the motorbike section. As demonstrated in Fig. 5, there are 10 motorbikes (N) set up in the motorbike section evenly (see the red section in Fig. 5). The section lengths (L) with motorbikes were set up as 10 m, 15 m, 20 m, and 30 m in different experiment cases. Therefore, the motorbike density (ρ_b) can express as $\rho_b = N / (wL)$ by considering the width (w) of the motorbike lane.

Moreover, since the influence of evacuee density and motorbike density on evacuation speed would both exist in the motorbike section, the function $V= V_0 f(\rho_e)$ in Section 4.1 should be further embedded the factor of motorbike density and be rewritten in the form of $V= V_0 f(\rho_e)\, g(\rho_b)$.

Figure 24 indicates that $g(\rho_b)$ was mainly divided into four groups as the four motorbike density was considered in experiments. Moreover, the distribution of data points in Fig.24 reveals that $g(\rho_b)$ gradually decreased with the increase of motorbike density. Thus, we further assume the function $g(\rho_b)$ in the following exponential form, as Eq 17.

$$g(\rho_b) = (1 - ae^{\frac{b}{\rho_b}}) \qquad \text{Eq. 17}$$

Where a and b are the parameter which affect the shape of the function $g(\rho_b)$. And then, we conducted the non-linear regression by applying the least square method to estimate the function $g(\rho_b)$. The regression curve is shown as the lines in Figure 24, and the regression function is generated as Eq. 18:

$$g(\rho_b) = \left(1 - 0.75e^{-\frac{0.48}{\rho_b}}\right) \qquad \text{Eq. 18}$$

The regression curve in Figure 24 is well fitted with the mean of the distribution of $g(\rho_b)$ in each motorbike density. But in the same motorbike density condition, the difference in individual evacuation speed still exists.

Moreover, it should be noted that an extreme situation is that motorbikes are probably congested in the lane so that people could not evacuate in the motorbike lane when a tunnel fire accident occurs. However, such motorbike density conditions have not been explored in the present experiment. Whether the current regression function could explain the evacuation speed under the condition of high motorbike density is unclear. Therefore, the regression function in Figure 24 only expressed the motorbike density around 0.50 motorbike /m^2 ($1/\rho_b$ =2 m^2/motorbike).

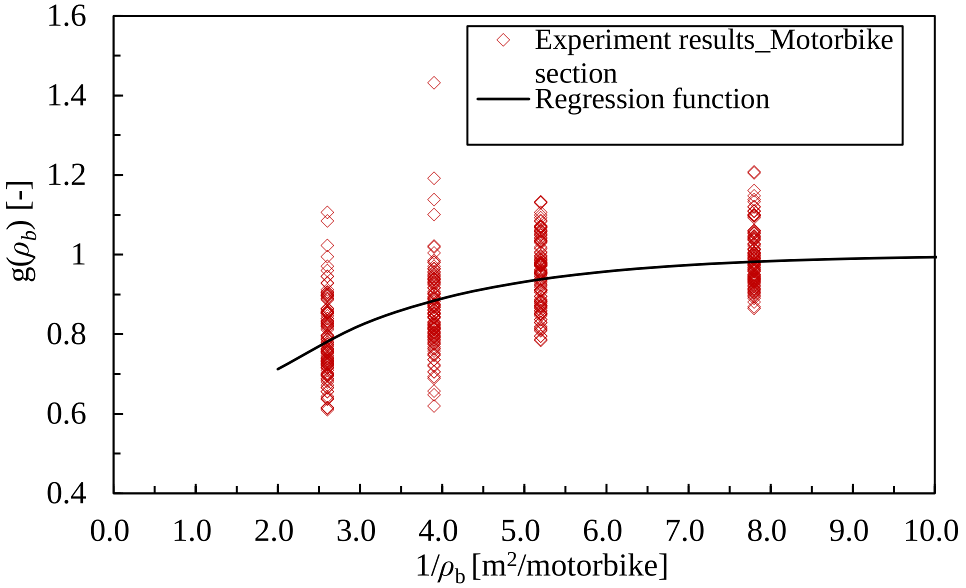


Figure 24 Relationship between g(ρb) and motorbike density (ρb)

4.2.3 Evacuation speed model and limitations

Since Figure 23 and Figure 24 reveal the relation between evacuation speed, evacuee density, and motorbike density, the function for modeling motorbike lane evacuation considering both the evacuee density and motorbike density can be expressed as the following function Eq.19:

$$V = V_0\left(1 - 0.32e^{-\frac{0.05}{\rho_e}}\right)\left(1 - 0.75e^{-\frac{0.48}{\rho_b}}\right) \qquad \text{Eq. 19}$$

To verify the model of evacuation speed, we apply Eq. (19) to estimate the evacuation speed and compare the measured evacuation speed in the present experiment. The V_0 is assumed 2.20 m/s. Each modeled evacuation speed is calculated based on the same condition of evacuee density and motorbike density from the measured evacuation speed. The modeled evacuation speed is shown on the *y*-axis and the measured evacuation speed is shown on the *x*-axis in Fig.25.

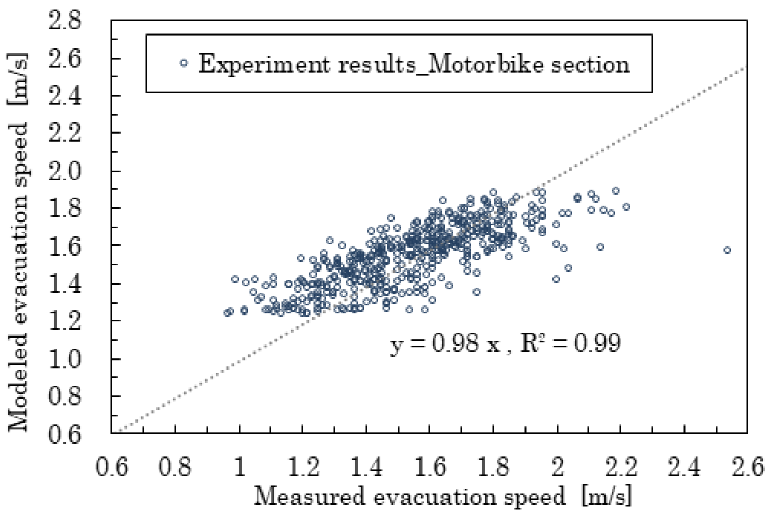


Figure 25 Measured evacuation speed and modeled evacuation speed

Modeled evacuation speed is in acceptable agreement with the speed in experiments.

Therefore, the regression model which considers variables of evacuee density and motorbike density could be an approach to reproducing the evacuation speed in the motorbike lanes in the tunnel.

Moreover, the variation of density in this study mainly depends on the designed "starting interval time" of 1 to 3 s, which causes the density range of the experiment to be concentrated in a relatively limited interval. The estimation of the parameters in the model should also be adjusted or revised when more samples from the experiment or observation were included. Nevertheless, the novelty of this study is proposing an evacuation model which could be regarded as a preliminary approach to explaining the evacuation behavior of motorbike lanes.

Furthermore, since the main purpose of the present study is to clarify the influence of evacuee densities, and motorbike densities on the evacuation speed in the motorbike lane, no discussion on individual differences in-depth. Therefore, further investigation on the influence of gender, body size, and age brackets on evacuation speed in the motorbike lane has not been clarified even though it is well-known that physical ability is different between gender, body size, and age brackets.

Regarding the factor of motorbike density, the evacuation speed in the condition of motorbike density larger than 0.38 motorbikes/m^2 has not been fully investigated through the present experiments. Further investigation of various population categories and motorbike density should be considered as a future task to enhance the reliability

Influence of evacuee density and motorbike density on evacuation speed

of evacuation models in motorbike lanes.

4.3 summary

In the research of this chapter, we use the least squares method to analyze the relationship between the evacuation speed and the density in the non-motorbike section and the motorbike section of the experimental site and establish a model. And the limitations of the experiment are explained. The main results are as follows:

1. We use the least squares method to propose the curve relationship between the evacuee density and the evacuation speed, and propose an exponential equation. This equation can reasonably explain that the speed of the non-motorbike section can also be observed under the condition of low evacuee density in the tunnel motorbike lane decreasing trend with increasing evacuee density.

2. Within the range of different densities, the mean evacuation speed is about 1.42-2.05 m/s. The mean and 95% CI evacuee (upper and lower) in the range of 0.0~0.05 persons/m^2 evacuee density were 2.05, 2.28, and 1.82 m/s, respectively. This result is close to the mean evacuation velocity in no-smoke conditions in the experimental investigations conducted by Seike et al. (2021) [7] and experiment results conducted

3. In order to further verify the proposed function of evacuee density and evacuation speed in the experiment, compare the root mean square error (RMSE) of other pedestrian model functions. As a result, the model function proposed in our experiment has the smallest root mean square error, indicating that it has a good fit

with the experimental data.

4. Use the least squares method to do non-linear regression on the relationship between the motorbike density and the evacuation speed in the experimental motorbike section. Considering that the influence of evacuee density and motorbike density on the evacuation speed will exist in the motorbike section, the motorbike density factor should be further embedded for the evacuee density, and evacuation speed function $V= V_0 f(\rho_e)$ will be rewritten as $V= V_0 f(\rho_e)\, g(\rho_b)$. From this, the non-linear regression curve equation is obtained, and the curve of motorbike density and speed is drawn.

5. Some limitations of the experiment are also proposed in the present study, including the evacuee density of the experiment is mostly concentrated in the low-density range. In addition, the motorbike density range is not greater than 0.38 motorbikes/m^2. No further surveys were made on participant categories. In the future, the above experimental limitations will be further investigated, and the evacuation model for evacuation speed in the tunnel motorbike lane will be more comprehensive.

6. The proposed model consisting of variables of the evacuee density, the motorbike density, and free walking speed provides a good representation of the evacuation speed in motorbike lane evacuation.

5. CONCLUSIONS

In the first chapter mentioned to promote tunnel fire safety, researchers in Europe and Japan have been working on the clarification of evacuation behavior during tunnel fires and leading the field. Other countries have almost taken the risk assessment approach and safety criteria of Europe, and Japan as the reference for determining tunnel fire safety strategies. Since the proportion of motorbikes is small in Europe and Japan, the evacuation safety of motorbike users was not included in the risk assessment in the event of a tunnel fire. However, in many Asian countries where the utilization ratio of motorbikes is extremely high, it is not uncommon for more than half of road users to be motorbike users. Once a fire accident occurs in the tunnel in countries with a high utilization ratio of motorbikes, there would be a higher risk than expected due to the tunnel involving additional motorbike users who need to evacuate. Motorbike lanes in the tunnel have the characteristics of narrow width, hundreds of meters distance, and the obstruction of motorbikes. The human density is relatively low as is not designed for dense crowd passing. Whether existing diagrams of speed-density and developed models could completely describe the walking speed characteristics in motorbike lanes is unclear. Therefore, the present study aimed at developing an evacuation model which considered the effect of motorbike density and evacuee density on the walking speed of motorbike users. This evacuation model will help develop the sub-evacuation model which can be applied to analyze the event of a tunnel fire in countries with a high motorbike utilization rate, and possibly to further improve the safety assessment process for tunnel fires.

CONCLUSIONS

Chapter two explains the experiment place selection, experimental design, experimental process and experimental cases. The motorbike flow and density analysis are also carried out for the actual traffic accident cases in the motorbike lane of the Kaohsiung Crossing Harbor Tunnel, and the calculation of the time interval of the specific section of the experiment is explained. The main results are as follows:

1. In the present research, we forced on two different factors that affect the speed of evacuation, one is evacuee density and the other is motorbike density. Therefore, we designed the departure interval time of each experimenter to be 1 second, 2 seconds, and 3 seconds to distinguish different evacuee densities. In addition, we design different motorbike densities to be 0.38, 0.26, 0.19, and 0.13 motorbikes/m2 to distinguish different motorbike densities.

2. The experimental results would only focus on discussing the relationship between walking speed and evacuee density, the influence of the different ages and genders could not be observed in the present experiments.

3. The motorbike flow rate in a traffic accident (0.12 motorbikes/s) was only around one-third of the flow rate in rush hour. it can expect that the difficulty in the motorbike lane evacuation would also increase once the fire occurs during rush hour. Furthermore, perform regression analysis on the number of motorbikes accumulated at 30-second intervals within 5 minutes after the actual traffic accident in the motorbike lane of the Kaohsiung Crossing Harbor Tunnel and the corresponding

distance, and the regression equation of y=0.98x-5.42 can be obtained. 5.42 meters means that the first motorbike stops approximately 5.42 meters from the starting point of the calculation. This result will be an important parameter for future safety assessment of tunnel motorbike lanes.

4. The analysis of this traffic accident revealed that motorbikes congested the lane, and the motorbike density reached a constant value with limited lane space. This indicates that motorbikes involved in a tunnel accident would result in the accumulated distance of motorbike congestion extending rather than the motorbike density increasing. This reflects the necessity of timely traffic control for motorbike lanes in an emergency to prevent an increase in tunnel users needing evacuation.

5. The time interval calculation of a specific section in the experiment has a great relationship with the calculation of the evacuee density. The time interval of each experimenter in a specific section is different from the time interval of departure. Through the study of the calculation method, the calculation of the personal time interval in a specific section can be confirmed, and then the personal evacuation density can be calculated.

In chapter three, we use the least squares method to analyze the relationship in normal walking speed between evacuee density and motorbike density in the non-motorbike section and motorbike section of the experimental site and establish a model. And the limitations of the experiment are explained. The main results are as follows:

CONCLUSIONS

1. We analyze the experimental data of the non-motorbike sections in the experiment, and use the least squares method to propose a curve relationship between evacuee density and the normal walking speed. Because the experimental data are in the low-density range, we use two-regime models to connect the curves between low-density and high-density. The results show that the curve of the relationship between density and speed and the model equation can reasonably explain the trend that the speed of non-motorbike sections in the tunnel motorbike lane decreases with the increase of density. To further verify the two-regime model, the root mean square error (RMSE) of models proposed by other studies was compared with present models. Compared with other models, the two-regime model proposed in this study has the smallest RMSE, indicating good fitness.

2. In the experimental motorbike section, we also use the least squares method to analyze the curve between motorbike density and normal walking speed; and propose a modeled exponential equation. This equation can also reasonably explain the trend that the normal walking speed of the motorbike section in the motorbike lane of the road tunnel decreases with increasing motorbike density.

3. Some limitations of the experiment are also proposed in the present study, including the evacuee density of the experiment is mostly concentrated in the low-density range. In addition, the motorbike density range is not greater than 0.38 motorbikes/m2. No further surveys were made on participant categories. In the future, the above experimental limitations will be further investigated, and the evacuation model for

normal walking speed in the tunnel motorbike lane will be more comprehensive.

In chapter four, we use the least squares method to analyze the relationship between the evacuation speed and the density in the non-motorbike section and the motorbike section of the experimental site and establish a model. And the limitations of the experiment are explained. The main results are as follows:

1. We use the least squares method to propose the curve relationship between the evacuee density and the evacuation speed, and propose an exponential equation. This equation can reasonably explain that the speed of the non-motorbike section can also be observed under the condition of low evacuee density in the tunnel motorbike lane decreasing trend with increasing evacuee density.

2. Within the range of different densities, the mean evacuation speed is about 1.42-2.05 m/s. The mean and 95% CI evacuee (upper and lower) in the range of 0.0~0.05 persons/m2 evacuee density were 2.05, 2.28, and 1.82 m/s, respectively. This result is close to the mean evacuation velocity in no-smoke conditions in the experimental investigations conducted by Seike et al. (2021) and experiment results conducted by Boer (2002).

3. In order to further verify the proposed function of evacuee density and evacuation speed in the experiment, compare the root mean square error (RMSE) of other pedestrian model functions. As a result, the model function proposed in our experiment has the smallest root mean square error, indicating that it has a good fit

with the experimental data.

4. Use the least squares method to do non-linear regression on the relationship between the motorbike density and the evacuation speed in the experimental motorbike section. Considering that the influence of evacuee density and motorbike density on the evacuation speed will exist in the motorbike section, the motorbike density factor should be further embedded for the evacuee density, and evacuation speed function V = V0 f(ρe) will be rewritten as V = V0 f(ρe) g(ρb). From this, the non-linear regression curve equation is obtained, and the curve of motorbike density and evacuation speed is drawn.

5. This chapter and Chapter 3 also propose some experimental limitations, including the evacuee density of the experiment is mostly concentrated in the low-density range. In addition, the motorbike density range is not greater than 0.38 motorbikes/m2. No further surveys were made on participant categories. In the future, the above experimental limitations will be further investigated, and the evacuation model for emergency evacuation walking speed in the tunnel motorbike lane will be more comprehensive.

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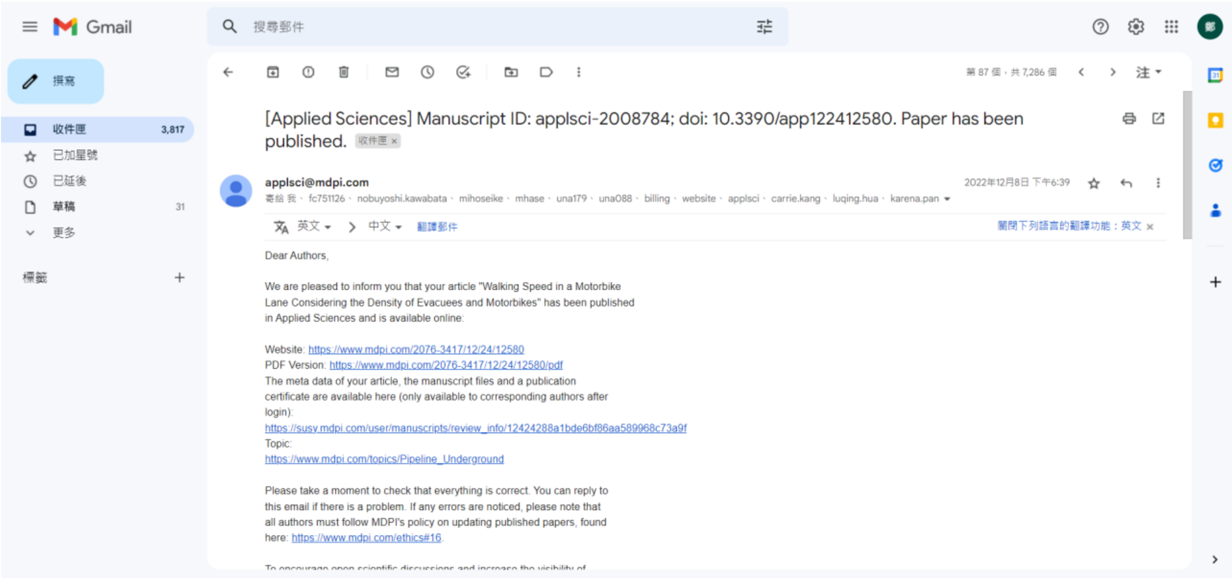

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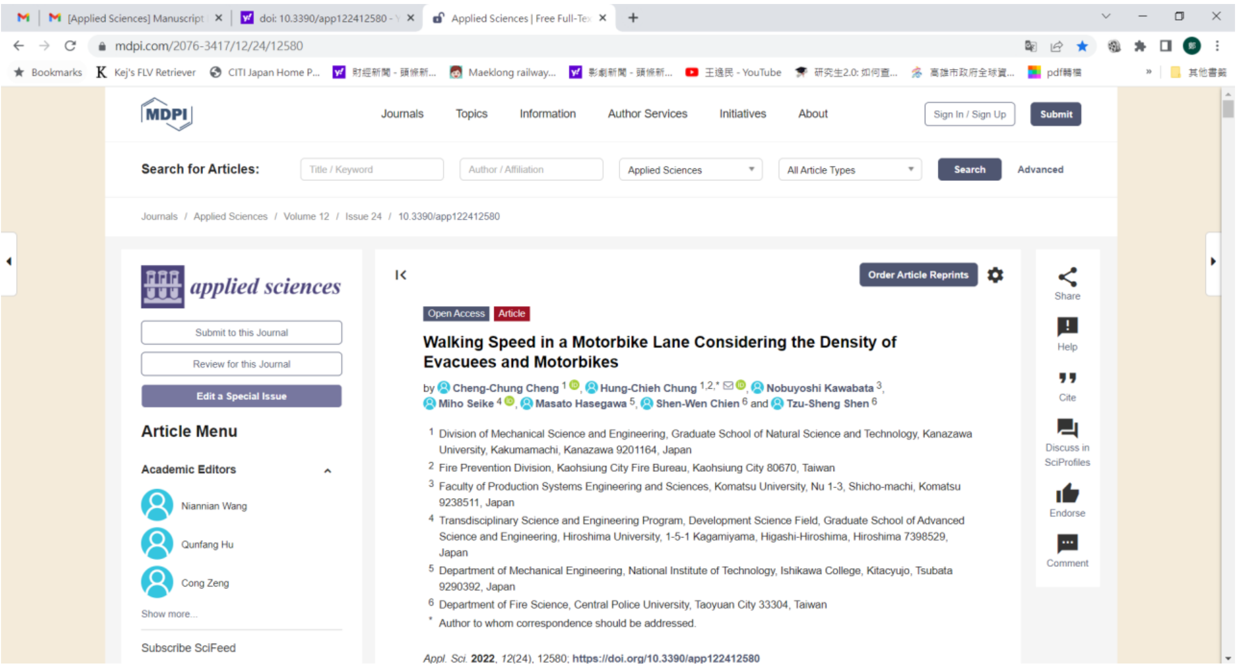

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