学　位　論　文　要　旨
Dissertation Abstract

学位請求論文（Dissertation）

題名（Title）Walking speed and evacuation speed of the motorbike lane by considering the density of evacuees and motorbikes

バイクレーンにおける歩行速度と避難速度に対する避難者およびバイク密度の影響

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Abstract:

In countries with a high motorbike utilization rate, road tunnels can feature motorbike lanes, bringing an additional risk to evacuation from tunnels during a fire or emergency. To better understand the walking speed in motorbike lanes to enhance risk assessment in tunnels, in the present study, we conducted evacuation experiments to investigate the influence of motorbike and evacuee density on the walking speed of motorbike users. According to the experimental results, the walking speed was slightly reduced even when the evacuee density was relatively lower (around 0.1 person/m^2). To further analyze the influence of motorbikes in the lane, the walking speed decreased significantly with the increase in motorbike density. The decrease in walking speed presented an exponential relationship with evacuee and motorbike density. Considering this exponential relationship, nonlinear regression was applied to estimate the parameters of the walking speed model. The proposed model consisting of the evacuee density, motorbike density, and free walking speed as variables can serve as an approach to describe the walking speed and evacuation speed of motorbike lane evacuation in tunnels.

1. Introduction

In the present study, with our investigation of the tunnels which allow motorbikes to pass, 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; and extra hazards(fire, explosion, serious traffic accidents, etc.) to users in car lanes. 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

However, take the Cross-Harbor tunnel as an example, 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, most studies of the speed-density relationship focused on the normal walking movement of pedestrians, rather than evacuation scenarios in tunnels.

Motorbike lanes in the tunnel have the characteristics of narrow width, hundreds of meters distance, and obstruction of motorbikes. The human density is relatively low as is not designed for dense crowd passing. 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. 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.

2. Motorbike lane evacuation experiment

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. 1). 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.

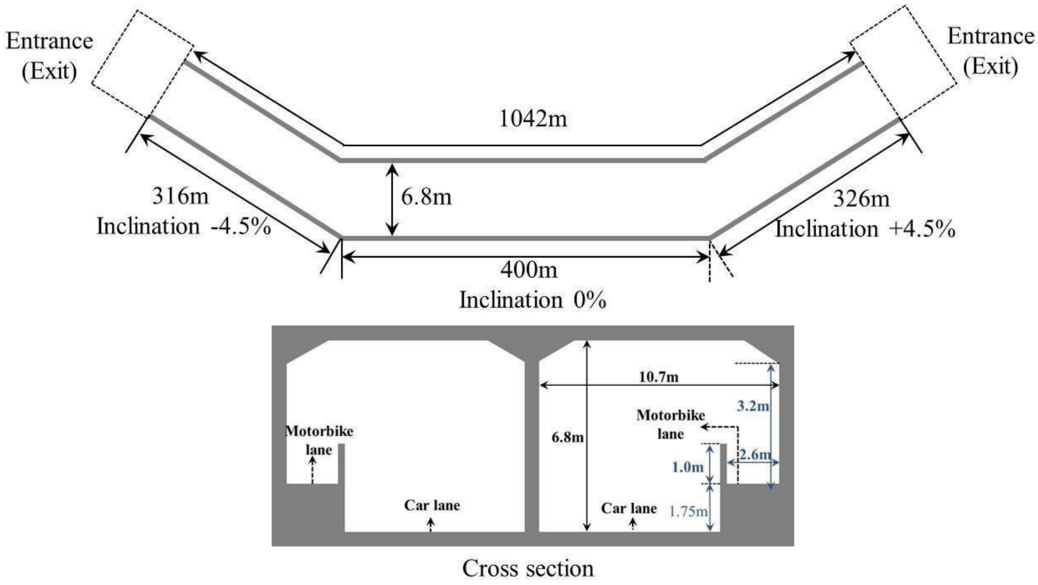

Figure 1 Cross-Harbor tunnel geometry

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 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/m2 to distinguish different motorbike densities. In this way, 24 experimental cases were designed. Figure 2 is a schematic of the experiment.

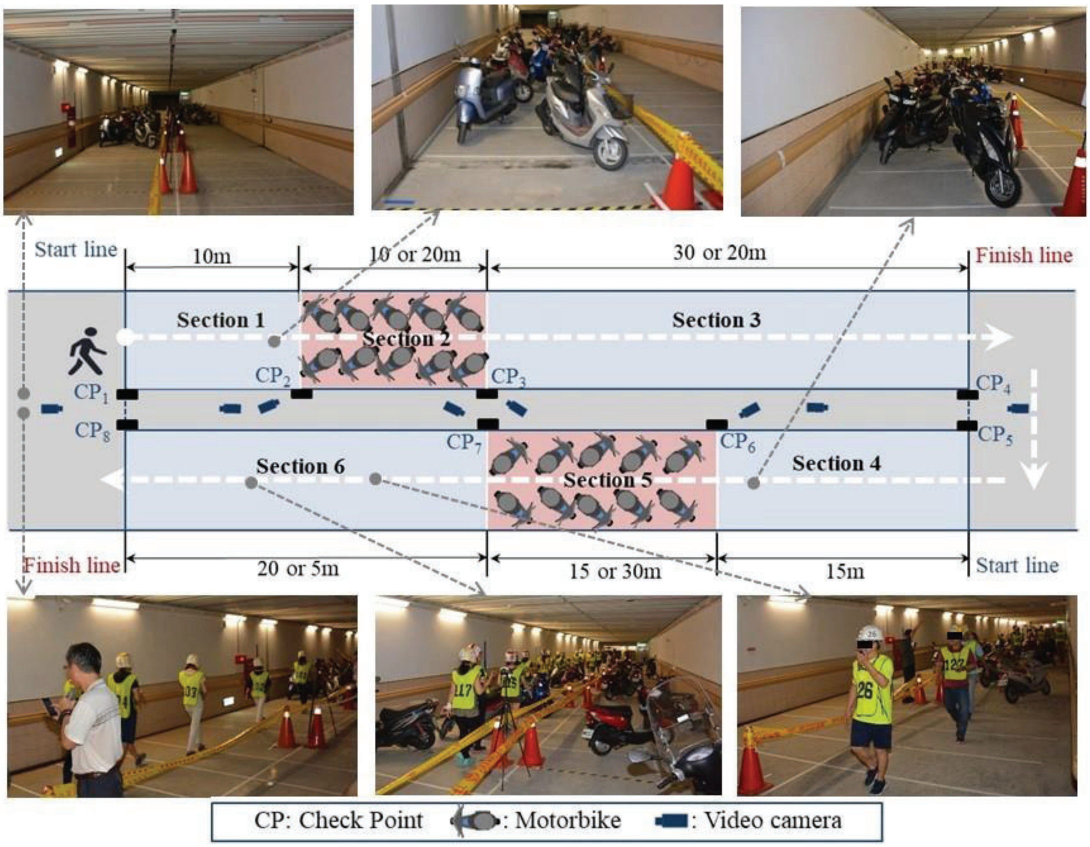

Figure 2 Schematic of motorbike lane experiments.

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 clarify. Therefore, the experimental results would only focus on discussing the relationship between walking speed and evacuee density. And the influence of body size on walking speed is insignificant.

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. The motorbike flow rate in a traffic accident (0.12 motorbikes/s) was only around one-third(0.35 motorbikes/s)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. This reflects the necessity of timely traffic control for motorbike lanes in an emergency to prevent an increase in tunnel users needing evacuation.

Moreover, we further show the cumulative motorbike number and corresponding accumulated distance in Figure 2. 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 3 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).

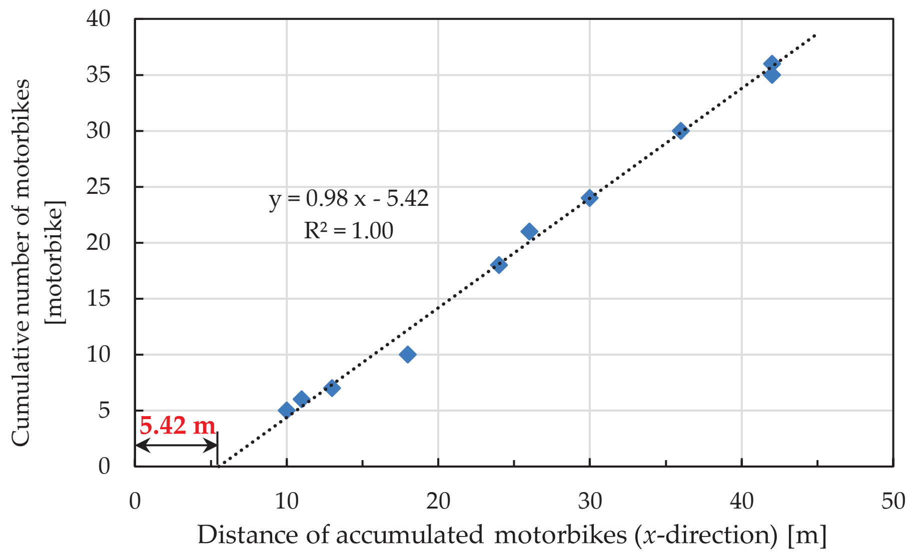

Figure 3 The cumulative motorbike number and corresponding accumulated distance.

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

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. Figure 4 reveals that the walking speed began to decrease when the density was around 0.4 person/m^2. 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.

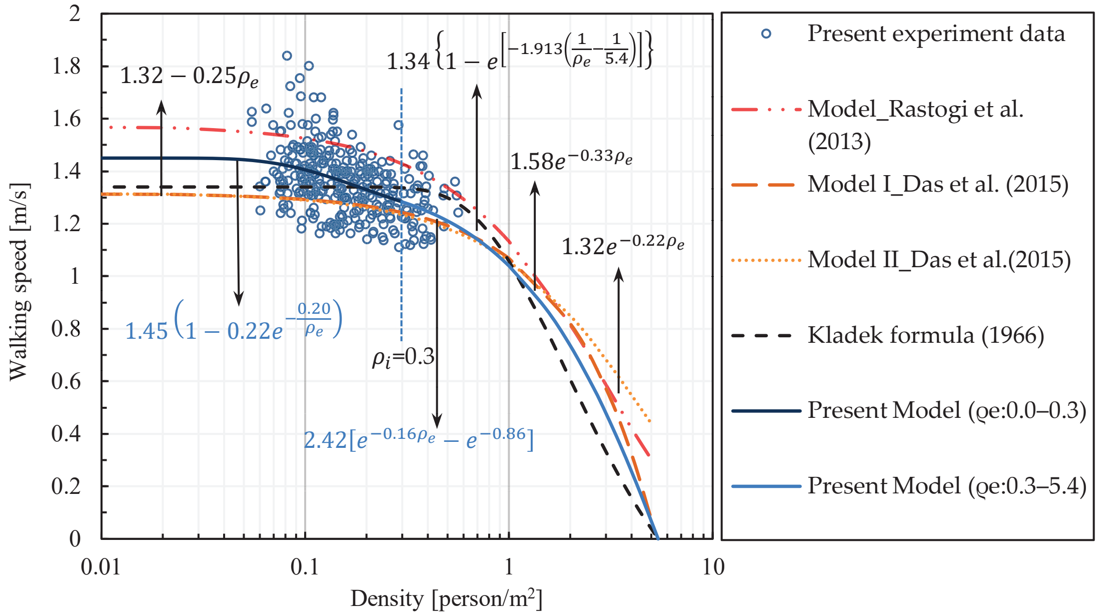

Figure 4 Speed-density relationship and modeling function.

To further verify the two-regime model, the root mean square error (RMSE) of models proposed by other studies was compared with present models(as Table 1). Compared with other models, the two-regime model proposed in this study has the smallest RMSE, indicating good fitness.

Table 1 RMSE between walking speed data and fitting model.

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

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(see Figure 5).

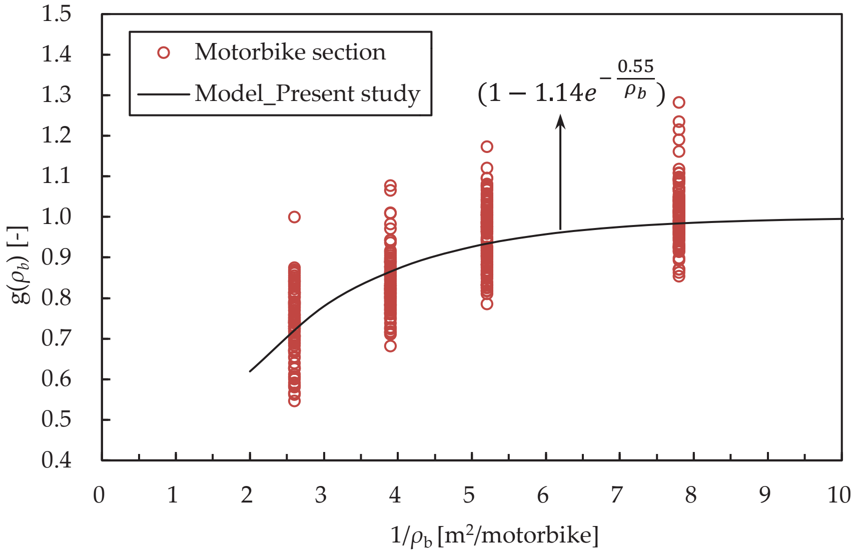

Figure 5 Relationship between g(ρb) and motorbike density (ρb).

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

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(see Figure 6).

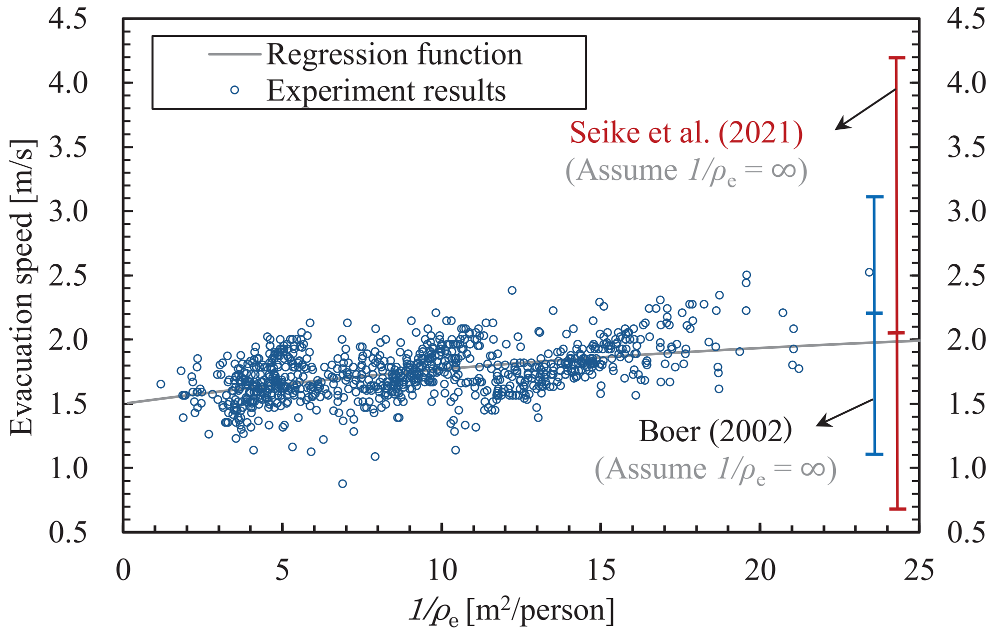

Figure 6 Speed distribution in the no-motorbike section and modeling function

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 the experiment results conducted by Boer (2002).

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 in Table 2). 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.

Table 2 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

In the experimental motorbike section, we also use the least squares method to analyze the curve between motorbike density and evacuation walking speed; and propose a modeled exponential equation. This equation can also reasonably explain the trend that the evacuation walking speed of the motorbike section in the motorbike lane of the road tunnel decreases with increasing motorbike density(see Figure 6).

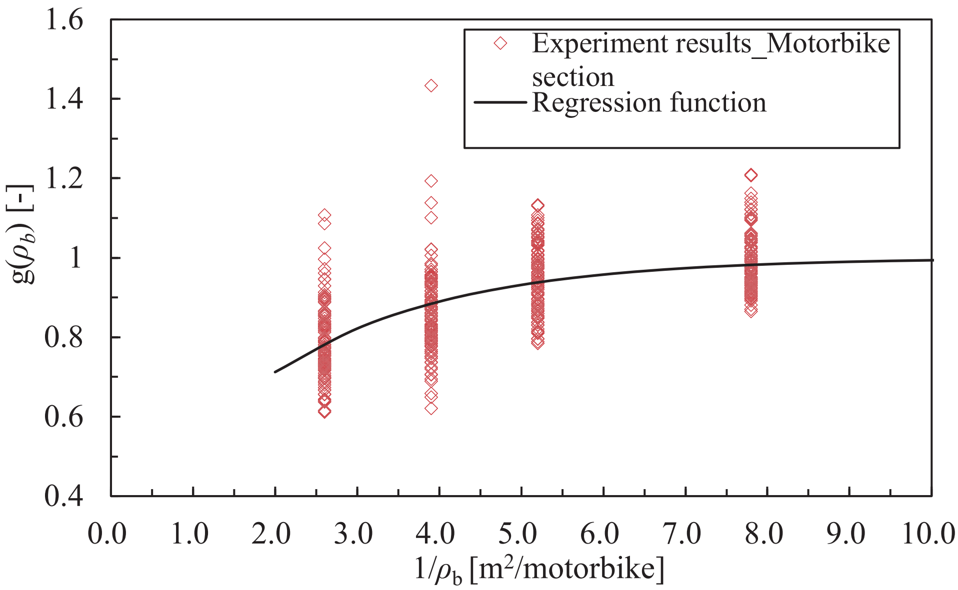

Figure 6 Relationship between g(ρb) and motorbike density (ρb)

5. CONCLUSIONS

The research findings are presented below.

1. The analysis of a past 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.

2. The experimental analysis clarified that the walking speed and the evacuation speed are reduced with the increases in motorbike density and evacuee density, even in conditions of low evacuee density (around 0.1 person/m2). The proposed exponential model consisting of the evacuee density, the motorbike density, and free walking speed as variables provides a good representation of the walking speed and evacuation speed in motorbike lane evacuation. The above findings contribute to expanding the understanding of evacuation behavior in the motorbike lane of a tunnel and arouse notice of motorbike lane evacuation issues for countries with high motorbike utilization.

3. Additionally, wider ranges of evacuee and motorbike density are still needed for evacuation

model calibration. The influence of various participant compositions on walking speed and evacuation speed has also yet to be studied. The development of an evacuation model that can be applied in lanes of mixed motorbikes and four-wheeled vehicles remains a future task that needs to be progressed.

令和　5年　2月　2日

学位論文審査報告書（乙）

1．学位論文題目（外国語の場合は和訳を付けること。）

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

（バイクレーンにおける歩行速度と避難速度に対する避難者およびバイク密度の影響）

2．論文提出者　ふりがな 氏名　鄭（つぇん） 震崇（つぇんちょん）

3．審査結果の要旨（600～650字）

当該学位論文に関し，令和5年1月26日に第1回学位論文審査委員会を開催し，提出された学位論文および関係資料について詳細に検討した．さらに，令和5年2月1日の口頭発表後に第2回学位論文審査委員会を開催し，慎重に協議した結果，以下の通り判定した．

台湾や東南アジアの国々の保有バイク数は極めて多く，道路交通の問題を考える場合にバイクの影響を考慮することは不可欠である．トンネル火災における避難対策においても同様であり，バイク利用者を含めた総利用者数による避難を考慮しなくてはならない．必然的にトンネル火災防災をリードしている欧米や日本とは異なる避難シナリオを構成する必要がある．本論文はそのような避難シナリオに必要なバイク利用者の避難速度について，被験者実験によって避難者の密度とバイクの密度が避難速度に与える影響を明らかにしたものである．被験者実験では，実際のトンネルにおけるバイクレーンでの事故の調査に基づいて実験条件を決めて計画を立てている．また，人の密度が極端に高くなった場合の歩行速度についての従来の実験式と本実験による歩行速度の式とを接続し，高密度の場合にも適用できる歩行速度予測式を提案している．

トンネル火災防災に関してバイク利用者を考慮した研究例はまだない．本論文は台湾などの保有バイク数の多い国々のトンネル火災防災対策の向上にとって極めて重要な貢献をするものと考えられる．したがって，工学的な寄与が大きく，博士（工学）の学位に値するものと判定した．

4．審査結果　(1) 判定（いずれかに○印）（合　格）・　不合格

(2) 授与学位　博　士（　工　学　）