Evaluating Collision Risk on Personal Mobility Vehicle Involved Shared Spaces

Charitha DIAS[1] and Miho IRYO-ASANO[2]

[1]Project Researcher, Institute of Industrial Science, The University of Tokyo
(4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan)
E-mail: cdias@iis.u-tokyo.ac.jp
[2]Associate Professor, Department of Environmental Engineering and Architecture, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan)
E-mail: m-iryo@urban.env.nagoya-u.ac.jp

Two-wheeled personal mobility vehicles (PMVs), such as Segway, are gaining popularity in recent years as an eco-friendly transport mode in urban environments. Japan and other Asian countries currently have some legal restrictions for riding Segway on shared walkways or bicycle lanes mainly because of safety issues. Nevertheless, discussions and proposals are underway in recent years to allow PMVs on shared spaces in Asian cities where pedestrian and cyclist demand is relatively high. Before authorizing PMVs on shared spaces in such cities safety of other road uses, mainly pedestrians and cyclists, should be appropriately evaluated. Surrogate safety measures may provide a flexible and convenient approach to assess safety on shared spaces. In this study, time-to-collision (TTC), Potential Index for Collision with Urgent Deceleration (PICUD) and maximum decelerations on Segway-bicycle and Segway-pedestrian shared spaces are analyzed with the data collected through controlled experiments conducted under various following situations. Results indicate that the collision risk on PMV and bicycle shared spaces could be significantly higher compared to PMV and pedestrian shared spaces. Further, as the collision risk is critical during sudden breaking situations, safety of shared spaces users may largely depend on the deceleration capabilities of PMVs.

Key Words : *Pedestrians, Bicycles, Segway, Mixed traffic, Time to collision, PICUD, Collision risk*

1. INTRODUCTION

Personal mobility vehicles (PMVs), such as Segway, are emerging as an eco-friendly alternative transport mode for short distance trips both in indoor and outdoor settings[1)]. These vehicles use electrical energy stored in rechargeable batteries and have been used in eco-tours in many cities around the world[1)]. Other than environmental benefits, PMVs provide numerous other benefits to the society and users[2)].

PMVs are allowed on shared sidewalks in many cities in Europe and the United States. Meanwhile, Japan and other Asian countries currently have some legal restrictions for riding PMVs on shared walkways or bicycle lanes mainly due to safety concerns. Nevertheless, discussions and proposals are underway to amend policies to allow PMVs on sidewalks in Asian cities as a versatile and eco-friendly alternative transport mode[3-4)]. It can be identified that pedestrian and cyclist demand is relatively high on sidewalks in Asian urban environments. Further, space is limited in urban environments in Asian cities to provide separate infrastructure for PMVs. Thus, the feasibility of allowing PMVs on existing infrastructure for pedestrians or bicycles should be examined. Before allowing PMVs on such shared environments, impacts of PMVs on other shared space users, i.e., pedestrians and cyclists, should be properly understood particularly in safety point of view.

Several studies can be found in the literature which investigated the safety aspects of PMVs. An early study by Goodridge[5)] examined the stopping sight distance (SSD) of Segway by utilizing data collected through field experiments. This study showed that the SSD of a Segway, operated by a college-age rider, can vary approximately from 7.6 m to 12.5 m when approaching at approximate speed of 20 km/h. That study further reported that the average reaction time for a Segway rider can vary between 0.6 s and 0.7 s. Further, the author has discussed potential accident types of PMVs using bicycle accident statistics. Through data collected from a field experiment, Landis et al.[6] showed that the average reaction time and deceleration rate for mixed-aged operators is 1.1 s (± 0.6 SD) and 3.1 m/s^2 respectively. Findings of these two studies[5-6] are considerably different as the experiment conditions were different. That is, the experiment by Goodridge[5] reflected sudden stopping conditions whereas experiment by Landis et al.[6] reflected general stopping conditions. Further, it can be noted that both these studied have not been conducted under mixed traffic conditions. Thus, may not be applicable in mixed traffic related practices. Dias et al.[7] analyzed perception-reaction times of Segway riders under different mixed traffic situations from the data collected through a controlled experiment. They considered pedestrian-Segway and bicycle-Segway traffic mixes under general continuous following situations as well as sudden breaking situations. As they reported, for both traffic mixes, reaction times of Segway riders were significantly smaller during sudden breaking situations compared to continuous following situations. Further, they described that Segway riders are more careful (i.e., smaller reaction times) when they follow cyclists than pedestrians. Nishiuchi et al.[8] conducted an experiment to investigate pedestrians' safe avoidance distance when confronting a Segway approaching at different speeds ranging approximately from 5 km/h to 20 km/h. They found that the safe avoidance distance of a standing pedestrian is increasing (approximately from 2.2 m to 5.5 m) with increasing approaching speed of the Segway. Dias et al.[9] utilized social force based microscopic simulation model, which was modified and calibrated for Segway and pedestrian mixed traffic[10], to evaluate safe avoidance of pedestrians when confronting an approaching PMV. Findings of these two studies[9-10] were consistent. Ito et al. [11] proposed a risk evaluation index using distance-based potential fields as an alternative collision risk index for pedestrian and PMV mixed traffic. Pham et al.[12] adopted the idea of personal space to simulate interactions between PMVs and pedestrians on shared spaces. They introduced invasion ration and crossing time of personal spaces of PMVs and pedestrians as indexes to describe the level of discomfort. All these experiment-based or simulation-based studies provide a general overview of the safety aspects of PMV maneuvers either under solo riding situations or when interacting with other road users. However, utilizing such approaches to assess safety of shared space users in terms of collision or accident risk may be difficult particularly in critical situations. Further, dynamically changing characteristics (due to evasive actions of the PMV rider) of collision risk may not be captured in such approaches. Existing safety indicators (e.g., time to collision (TTC)[13], Potential Index for Collision with Urgent Deceleration (PICUD)[14]), which have widely been utilized in safety analyses in vehicular traffic, may provide a promising approach to evaluate safety on PMV involved shared spaces as well. Further, evaluating such safety indices could be useful in additional applications such as developing collision avoidance systems and optimizing safety features of PMVs. Considering such possibilities, this study aims at exploring TTC, PICUD and decelerations in different Segway related mixed traffic conditions (i.e., Segway-pedestrian and Segway-bicycle). Data collected through controlled experiments for different following situations (i.e., continuous following and sudden breaking) were considered in this study. Details of these experiment design and considered scenarios are briefly discussed in the next section.

2. EXPERIMENTS

A series of controlled experiment was conducted at Chiba Experiment Station of the University of Tokyo during 4 days in November and December 2015. During each day, 6 people (i.e., 4 people for riding a Segway and 2 people for walking or cycling) took part in these experiments. Participants' age ranged approximately from 20 to 30 years. As participants were beginners for riding Segway a basic training was provided by trained Segway instructors until they were adequately familiarized to ride a Segway. Various scenarios related to avoiding, overtaking and following, which are possible interaction types in mixed traffic situations, were considered as follows:

A. Avoiding

A-1. A Segway rider is avoiding a confronting pedestrian

A-2. A Segway rider is avoiding a standing pedestrian

B. Overtaking

B-1. A Segway rider is overtaking a walking pedestrian

C. Following

C-1. A Segway rider is continuously following a walking pedestrian or cyclist

C-2. A Segway rider is continuously following a walking pedestrian or moving cyclist until the pedestrian or cyclist suddenly stops

Out of these experiments, "following" experiment scenarios, of which the current study is based on, were conducted on wide corridor of 2.5 m wide (see Figure 1 and 2) to replicate a Segway rider following a cyclist and a pedestrian. In PMVs following cyclist scenarios, the movement of Segway and the cyclist were started at the same time. Cyclists were instructed to maintain a constant speed (approximately 10 km/hr). In PMVs following pedestrian experiments, the pedestrian was instructed to walk at normal speed. Estimated average walking speed for pedestrians in these experiments was approximately varied from 1.3 m/s to 1.5 m/s. The PMV rider was signaled to start after the pedestrian has moved 10-12 m forward. In sudden stopping scenarios, the pedestrian or the cyclists were instructed to stop at a predetermined location whereas the PMV rider was instructed to follow and not to overtake the pedestrian or the cyclist. A detailed description regarding experiment design and procedures, considered experiment scenarios and data extraction methods can be found in Iryo et al.[15]. Figure 1 shows a schematic diagram of the experiment set-up. Figure 2 shows snapshots taken during "following" experiments.

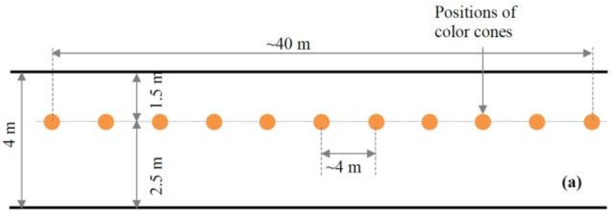

Fig.1 Schematic diagram of the experiment course with dimensions.

The position and time of each PMV, cyclist and pedestrian were extracted using a video image-processing system, called the TrafficAnalyzer[16]. In this study, only the data collected for following scenarios were used. The time resolution of the extracted trajectory data was 0.1 s. How these trajectory data were used to estimate TTC is discussed in the following section.

3. ESTIMATION OF SAFETY INDICES

In this study, time-to-collision (TTC) and potential index for collision with urgent deceleration (PICUD) for different following situations were explored. TTC is a time-based surrogate safety measure and can be considered as one of the most widely used safety indicators to measure the crash risk. PICUD is a distance-based surrogate safety measure and as the name implies it is used to evaluate mainly the rear-end collision risk under sudden deceleration situations.

Fig.2 Snapshots during Segway following a pedestrian (up) and Segway following a cyclist (down) experiments.

TTC is defined as the time required for two vehicles to come into a collision if they continue at their present speed and on the same path[13]. According to the TTC concept, TTC is estimated for each time step (i.e., as a time series) along a particular road section. A threshold TTC value is also defined to indicate the boundary between safe and unsafe traffic operations.

For rear-end collisions (Figure 3), which are common in following situations, TTC is calculated as follows:

$$\mathrm{TTC}(t) = \frac{X_L(t) - X_F(t) - l_L}{\dot{X}_F(t) - \dot{X}_L(t)} \ ; \ \forall \dot{X}_F(t) > \dot{X}_L(t) \qquad (1)$$

where, X denotes the position, $\dot{X}$ denotes the speed and l is the length of vehicle. The subscripts *"L"* and *"F"* indicate the leading vehicle and the following vehicle respectively. Note that the numerator of this equation represents the following gap or spacing between consecutive vehicles.

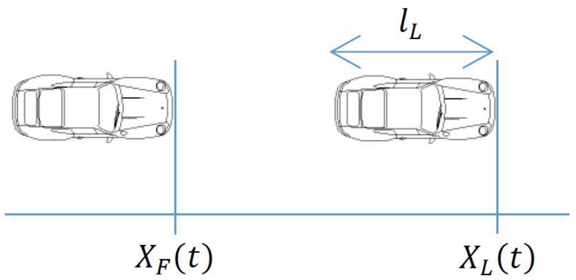

Fig.3 Calculation of TTC for following vehicles.

For rear-end collisions PICUD is calculated as follows:

$$\mathrm{PICUD}(t) = \frac{V_{L,t}^2}{2a_L} - \left(V_{F,t}\Delta t + \frac{V_{F,t}^2}{2a_F}\right) + S_0 \qquad (2)$$

where, $V_{L,t}$ is the speed of leading vehicle at time t, a_L is the deceleration rate of leading vehicle, $V_{F,t}$ is the speed of the following vehicle at time t, a_F is the deceleration of following vehicle, Δt is the reaction time of following vehicle and S_0 is the distance between leading and following vehicles.

The data used in this study consist of three types of agents, i.e., Segway, bicycles and pedestrians. Trajectory data extracted for Segway riders, cyclists and pedestrians were based on the wheel contact point with the road, front wheel contact point with the road, midpoint of the foot contact points of the road respectively. Thus, the numerator of Equation 1 and S_0 in Equation 2 were modified accordingly to represent the spacing between agents in following situation (Segway and bicycle or Segway and pedestrian) utilizing other information, such as length of the bicycle used in this experiment (approximately 1.7 m), footprint of the Segway model PT i2 used in this experiment (W 63 cm x L 48 cm)[1] and stride length of an average Japanese pedestrian (approximately 70 cm)[17]. Based on such modifications and utilizing instantaneous speed and maximum deceleration information, TTC and PICUD time series were obtained for all following experiments (Scenario C-1 and C-2). Results obtained through analyzing those TTC and PICUD time series for different following situations are discussed in the next section.

4. RESULTS AND DISCUSSION

(1) TTC

Examples of TTC time series for a Segway following a pedestrian case and a Segway following a cyclist case are shown in Figure 4 and Figure 5 respectively along with speed profiles of Segway, bicycle and pedestrian.

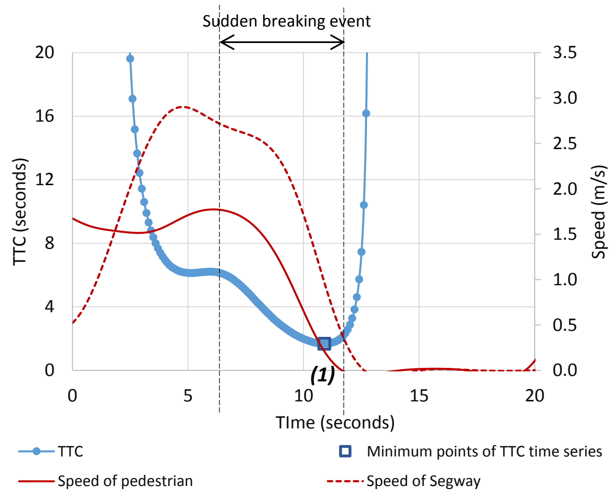

Fig.4 Time series of time-to-collision (TTC) and speed profiles for a Segway following a pedestrian case in Scenario C-2.

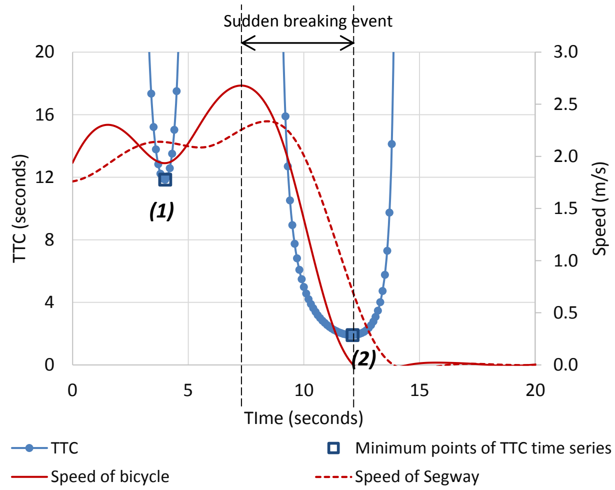

Fig.5 Time series of time-to-collision (TTC) and speed profiles for a Segway following a cyclist case in Scenario C-2.

Figures 4 and 5 describe that TTC is continuously changing with time as relative speeds and distances are changing. Local minimum points of the TTC time series, which are indicated with numbers, represent the most critical situations. Closely observing Figures 4 and 5, it can be understood that the most critical (or the most unsafe) instant, indicated by the minimum TTC, occurs during the sudden break event by the pedestrian or cyclist followed by the Segway rider. As the follower (i.e., Segway rider in these cases) takes evasive actions (i.e., generally, breaking in following situations) potential collisions can be avoided.

The relationship between relative speed and spacing for the Segway following a pedestrian case and Segway following a cyclist case (discussed in Figure 4 and 5) are shown in Figure 6 and Figure 7 respectively. Observing the marked minimum points on Figures 6 and 7 of the TTC time series, it can be noted that the minimum TTC occurs when Segway rider decelerates after the sudden break even by the leading pedestrian or cyclist.

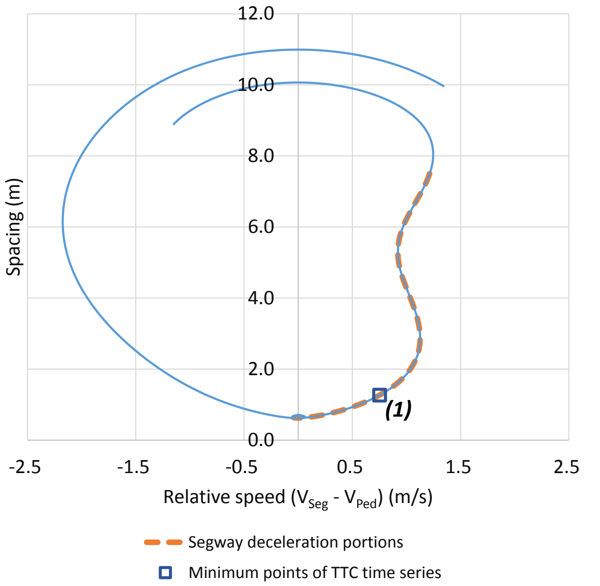

Fig.6 Relative speed and spacing relationship during a Segway following pedestrian case.

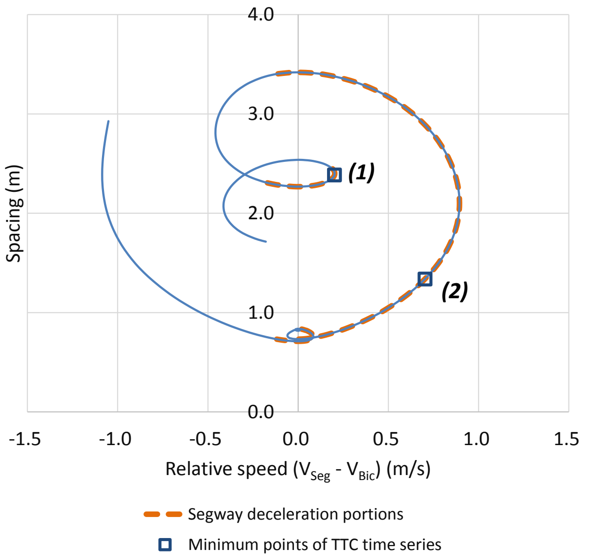

Fig.7 Relative speed and spacing relationship during a Segway following cyclist case.

Distributions for minimum TTC for a Segway following a pedestrian and a Segway following a cyclist cases (for experiments in Scenario C-2) are compared in Figure 8. Sample sizes for these cases were 21 and 28 respectively. Average (± standard deviation) of minimum TTC for a Segway following a pedestrian case and a Segway following a cyclist case were estimated as 2.82 (±1.04) s and 2.08 (±1.06) s respectively. Statistical tests confirmed that the difference of these mean TTC values are statistically significant at the 5 % level (Mann-Whitney U test z-score = 2.31, p = 0.02). This finding demonstrates that collision risk on Segway and bicycle shared spaces could be larger compared to Segway and pedestrian shared spaces.

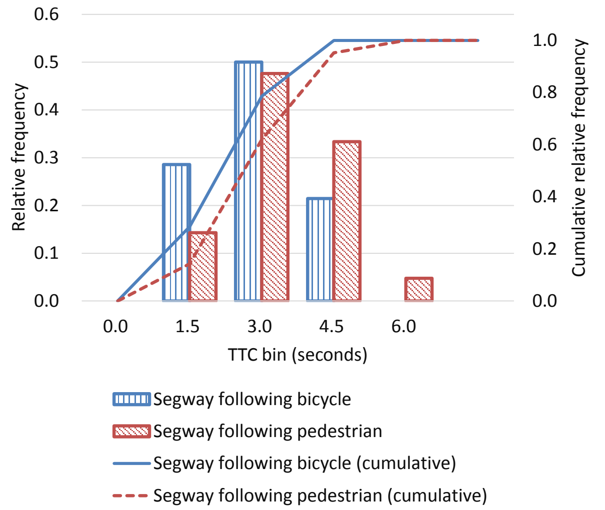

Fig.8 Comparison of minimum TTC distributions for Segway following bicycle and Segway following pedestrian cases during sudden breaking situations (Scenario C-2).

Figure 8 further describes that minimum TTC is less than 1.5 s for approximately 15% and 30% of cases of Segway following a pedestrian and Segway following a cyclist cases respectively. This TTC value (1.5 s) have previously been used as a threshold value in conflict analysis tools for vehicular traffic, for example, surrogate safety assessment model (SSAM)[18] and bicycle-car mixed traffic situations[19]. Based on such information, it can be explained that conflicts are more frequent on Segway and bicycle shared spaces compared to Segway and pedestrian shared spaces.

Figure 8 represents the most critical situations in considered following scenarios in these experiments (i.e., Scenario C-2 or following with a sudden break). Minimum TTC values for all cases combined (i.e., Scenario C-1 and C-2) were obtained from respective TTC time series for each case. For such general situations, average (± standard deviation) of minimum TTC for a Segway following a pedestrian case and a Segway following a cyclist case were estimated as 4.13 (±1.54) s and 5.29 (±3.30) s respectively (sample sizes were 53 and 74 respectively). The difference in mean TTC values was not statistically significant as confirmed with the Mann-Whitney U test (Z-Score = 1.45, p = 0.15).

(2) Acceleration and deceleration behavior

Acceleration profiles of Segway riders in different following situations were also analyzed. Figures 9 and 10 depict acceleration profiles and TTC for two experiment cases (same cases shown in Figure 4 and 5) of scenario C-2.

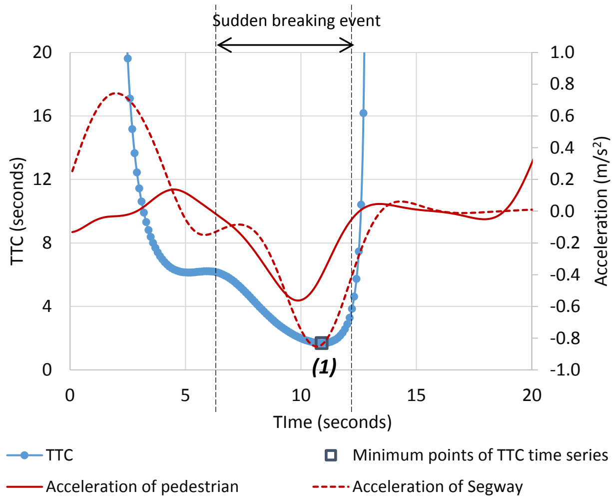

Fig.9 Time series of time-to-collision (TTC) and acceleration profiles for a Segway following a pedestrian case in Scenario C-2.

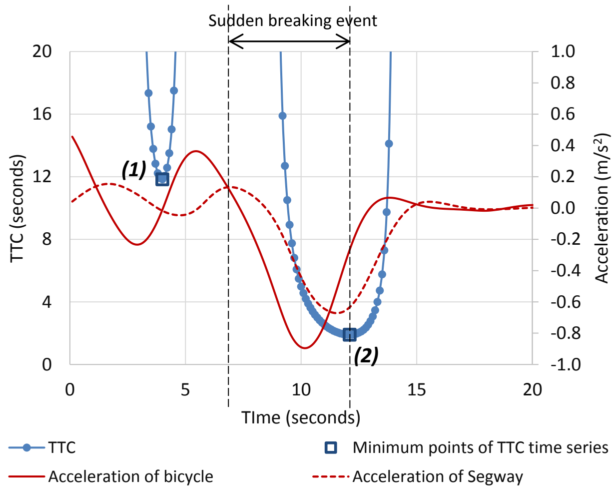

Fig.10 Time series of time-to-collision (TTC) and acceleration profiles for a Segway following a cyclist case in Scenario C-2.

As can be understood from Figures 9 and 10, deceleration of Segway is maximum in the vicinity of the minimum point of the TTC time series. That is, the collision risk on shared spaces might largely be determined by the deceleration capabilities of PMVs in addition to the perception reaction time of the Segway rider. Relationships between maximum deceleration and minimum TTC for a Segway following a pedestrian and a Segway following a cyclist were also compared with best fit curves as shown in Figure 11. For both following situations, the downward trend, i.e., decrease in minimum TTC with increasing maximum deceleration, can be described from this figure. However, no strong correlation was found between maximum deceleration and minimum TTC for both cases.

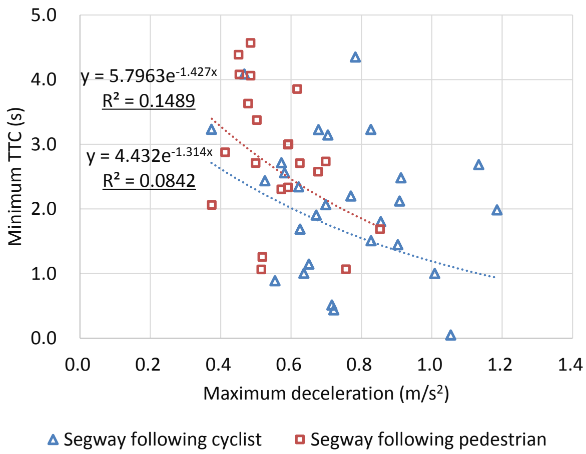

Fig.11 Relationship between maximum deceleration and minimum TTC for Segway following bicycle and Segway following pedestrian cases during sudden breaking situations (Scenario C-2).

Distributions for maximum deceleration values for a Segway following a pedestrian and a Segway following a cyclist cases in Scenario C-2, which is the most critical scenario with a deceleration with a sudden break, are compared as shown in Figure 12. Sample sizes for these cases were 21 and 28 respectively.

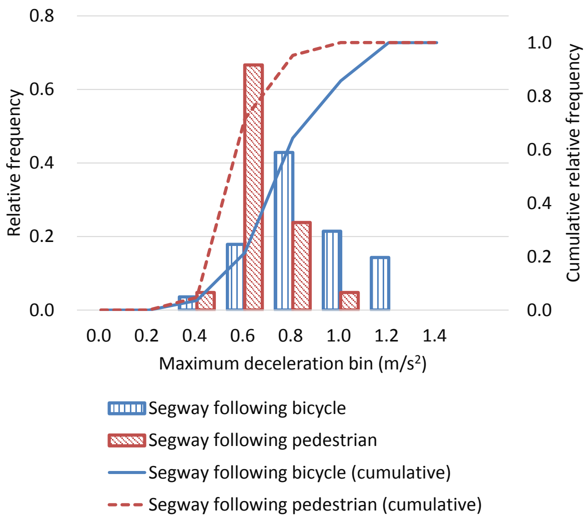

Fig.12 Comparison of maximum deceleration distributions for Segway following bicycle and Segway following pedestrian cases during sudden breaking situations (Scenario C-2).

Average (± standard deviation) of maximum deceleration values for a Segway following a pedestrian case and a Segway following a cyclist case were estimated as 0.56 (± 0.12) m/s^2 and 0.75 (± 0.20) m/s^2 respectively. Statistical tests confirmed that the difference of the means of minimum deceleration values are statistically significant at the 5 % level (Mann-Whitney U test z-score = 3.64, p = 0.0003).

(3) PICUD

PICUD values for Scenario C-1 were also estimated as a time series using Equation 2 to evaluate whether the Segway riders display safe behaviors during general following (without sudden break) situations. For these calculations maximum deceleration values for Segway riders when following pedestrians and cyclists were extracted from corresponding Scenario C-2 (i.e., 0.56 (± 0.12) m/s^2 and 0.75 (± 0.20) m/s2 respectively as discussed in previous section and in Figure 12). Estimated maximum average deceleration values for cyclist and pedestrians for sudden deceleration situations (Scenario C-2) were 0.81 (± 0.22) m/s^2 and 0.45 (± 0.13) m/s^2 respectively. Reaction time for Segway riders was set as 1.1 s based on the findings of previous studies[6,7] for general following situations. Two examples for PICUD time series for Segway rider following a cyclist case are shown in Figure 13. Minimum PICUD and corresponding minimum TTC for the same case are also shown on the graph.

Distributions of minimum PICUD values for a Segway following a pedestrian and a Segway following a cyclist cases were obtained and compared as depicted in Figure 14. Sample sizes for these cases were 26 and 28 respectively. Average (± standard deviation) of minimum PICUD values for a Segway following a pedestrian case and a Segway following a cyclist case were estimated as -0.88 (±1.10) m and -1.17 (±1.61) m respectively. Although the average PICUD is smaller for PMV following cyclist case, statistical tests confirmed that the difference of these mean PICUD values are not statistically significant at the 5 % level (Mann-Whitney U test z-score = 0.48, p = 0.63). These statistics, based on PICUD, demonstrate that the Segway rider behavior may not be safe (as the average PICUD values for both cases are less than zero) on pedestrian-Segway as well as bicycle-Segway shared spaces even under general following situations when they do not expect a sudden deceleration by the leading pedestrian or cyclist.

It should be noted that the experience of Segway riders may have considerable influence on these results. All participants (Segway riders) of these experiments were beginners. As confirmed by Nishiuchi et al.[20] experienced riders can decelerate smoothly compared to beginners. That means experienced riders can adjust acceleration and deceleration behaviors in a way that they can avoid any collision caused by sudden break by the leading pedestrian or cyclist. Further, Segway riders in this experiment (Scenario C-1) knew that there was no any sudden breaking situation in these experiment runs (as there was Scenario C-2 with sudden deceleration). Thus, they have not been prepared for any sudden deceleration situation under such experiment conditions and they are more relaxed in Scenario C-1 compared to Scenario C-2.

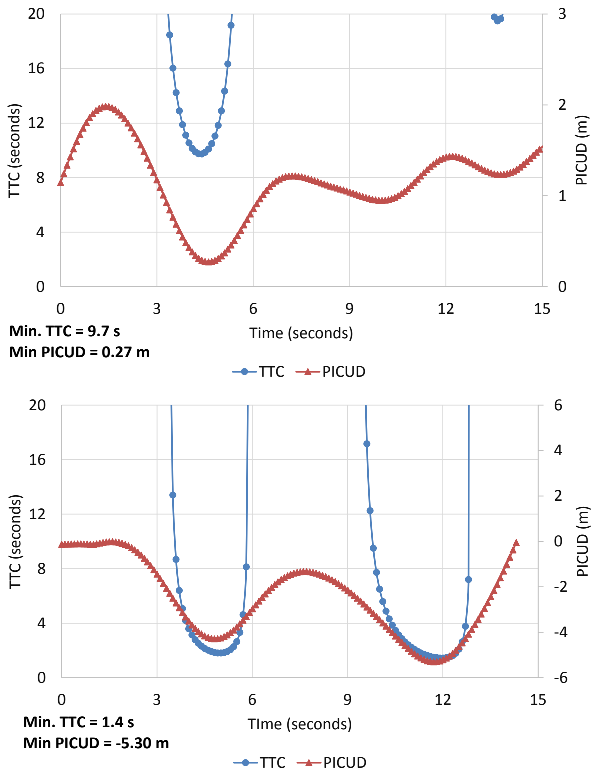

Fig.13 Variation of TTC and PICUD time series and their correlation.

Additionally, Segway riders' reaction times are also significantly larger under general following conditions compared to sudden breaking situations[7]. Such findings in previous studies further suggest that when Segway riders are prepared for any unsafe situations their reaction times could be lower (i.e., more conservative behavior) compared to unprepared situations. Generally, in real world situations, Segway riders are more prepared and alert to face any unsafe situations compared to experiment situations, particularly in situations equivalent to Scenario C-1. Due to such dissimilarities between experiment conditions and equivalent real world situations, there is a possibility that PICUD estimates in this study represent underestimated values.

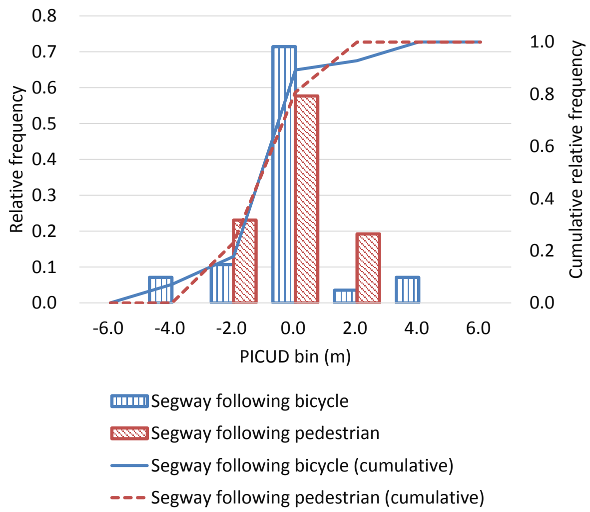

Fig.14 Comparison of minimum PICUD distributions for Segway following bicycle and Segway following pedestrian cases during general following situations (Scenario C-1).

5. CONCLUSIONS

Although two-wheeled personal mobility vehicles, such as Segway, have been identified as an eco-friendly vehicle, these are not currently allowed on shared spaces in Japan as well as in other Asian countries mainly due to safety concerns. Existing risk evaluation indices (e.g., TTC and PICUD) and deceleration behavior, which have been extensively used in safety analysis in vehicle traffic, could be used to evaluate collision risks on Segway related shared spaces as well. In this study, TTC, PICUD and maximum decelerations (obtained from data collected through controlled experiments) were analyzed for different following situations (i.e., a Segway following a pedestrian and Segway following a cyclist under general following and sudden decelerating situations). As results suggest, collision risk on Segway and bicycle shared spaces could be larger compared to Segway and pedestrian shared spaces particularly in critical situations (e.g., sudden break and stop by the leading pedestrian or cyclist). Further, it was clarified that the deceleration capabilities of PMV may have large impacts on safety on shared spaces.

It should be noted that the experiment participants were beginners for riding Segway. Experienced riders could control a PMV better and safer compared to beginners. Further, in these experiments, only two shared space users (i.e., a Segway rider and a pedestrian or a cyclist) were considered at a time. Segway riders' behavior could significantly differ when they interact with multiple pedestrians or cyclists or both. Additional empirical studied are needed to confirm such effects.

Comprehensive empirical statistics and findings of this study may assist authorities for evaluating shared road designs and implementation policies and PMV manufacturers to design PMVs with improved safety features.

ACKNOWLEDGMENTS: This research is supported by JSPS KAKENHI Grant Number 16K14317 as well as the special research fund of Institute of Industrial Science, The University of Tokyo. Further, authors would like to thank Associate Professor Kimihiko Nakano at Tokyo University and Assistant Professor Keisuke Shimono at Tokyo University of Agriculture and Technology for their support for organizing the experiment.

REFERENCES

1) Personal Transportation That Simply Moves You _ Segway, http://www.segway.com/, Accessed on 10/05/2016.
2) Ulrich, K. T. (2005). Estimating the technology frontier for personal electric vehicles. *Transportation research part C: Emerging technologies*, 13(5), 448-462.
3) Hashimoto N., Tomita K., Boyli A., Matsumoto O., Smirnov A., Kashevnik A., & Lashkov I. (2015). Operational Evaluation of New Transportation Method for Smart City: Use of Personal Mobility Vehicles under Three Different Scenarios. *Proceedings of the Fourth International Conference on Smart Systems*, Devices and Technologies, Brussels, Belgium, 1–6.
4) Channel News Asia. Allow bicycles, personal mobility devices on footpaths, but with speed limits_ Advisory panel, March 2016, http://www.channelnewsasia.com/news/singapore/allow-bicycles-personal/2611700.html. Accessed May 10, 2016.
5) Goodridge S. G. (2003) The Segway Is a Vehicle: Implications for Operation and Regulation of the EPAMD in Traffic, HumanTransport.org (www.humantransport.org/bicycledriving/library/segway/Segway.htm), Accessed on May 10, 2016.
6) Landis, B., Petritsch, T., Huang, H., & Do, A. (2004). Characteristics of emerging road and trail users and their safety. *Transportation Research Record: Journal of the Transportation Research Board*, 1878, 131-139.
7) Dias, C., Iryo-Asano, M., Shimono, K., & Nakano. K. (2017). Experimental Analysis of Segway Rider Behavior under Mixed Traffic Conditions. *Seisan Kenkyu*, 69(2), 81-85.
8) Nishiuchi, H., Sato, T., Aratani, T., & Todoroki, T. (2010) An analysis of Segway behavior focusing on safety distance for pedestrians and gaze of riders. *In Proceedings of the 17th World Congress on Intelligent Transportation Systems.*. Busan, Korea.
9) Dias, C., Iryo-Asano, M., & Nishiuchi, H. (2017). Evaluation of Safe Avoidance Distance for Pedestrians in Personal Mobility Vehicles and Pedestrian Mixed Traffic: A Simulation Based Study. *12th International Conference of Eastern Asia Society for Transportation Studies*, Ho Chi

Minh City, Vietnam.
10) Dias, C., Iryo-Asano, M., Shimono, K., & Nakano. K. (2017). Calibration of a Social Force-based Shared Space Model for Personal Mobility Vehicle and Pedestrian Mixed Traffic. *In 96th Transportation Research Board TRB Annual Meeting*..
11) Ito, T., Shino, M., & Kamata, M. (2011). Risk Evaluation Index of Low-Speed Vehicle Driving on Pedestrian Spaces. *Journal of Mechanical Systems for Transportation and Logistics*, 4(1), 24-38.
12) Pham, T. Q., Nakagawa, C., Shintani, A., & Ito, T. (2015) Evaluation of the effects of a personal mobility vehicle on multiple pedestrians using personal space. *IEEE Transactions on Intelligent Transportation Systems*, 16(4), 2028-2037.
13) Hayward, J. (1971). Near misses as a measure of safety at urban intersections. Ph.D. thesis, Dept. of Civil Engineering, The Pennsylvania State University, USA.
14) Uno, N., Iida, Y., Yasuhara, S., & Suganuma, M. (2002). Traffic Conflict Analysis and Modeling of Vehicle Speed Adjustment at Weaving Section. *Proceedings of Infrastructure Planning*, Vol.25, 4pages.
15) Iryo, M., Dias, C., Kato, H., Shimono K., & Nakano, K. (2016). Experimental Analysis of Personal Mobility Maneuver Reacting to Pedestrians and Cyclists. *Seisan Kenkyu*. 68(4), pp. 281-284.
16) Suzuki, K., & Nakamura, H. (2006). TrafficAnalyzer-the integrated video image processing system for traffic flow analysis. *In Proceedings of the 13th World Congress on Intelligent Transportation Systems.* London, (8 pp. in CD-ROM).
17) Sato, H., & Ishizu, K. (1990). Gait patterns of Japanese pedestrians. *Journal of human ergology*, 19(1), 13-22.
18) Gettmann, D., L. Pu, T. Sayed & S. Shelby. Surrogate Safety Assessment Model and Validation: Final Report. Publication FHWA-HRT-08-051. *FHWA*, *U. S. Department of Transportation*, 2008.
19) Zangenehpour, S., Strauss, J., Miranda-Moreno, L.F. & Saunier, N. (2016). Are signalized intersections with cycle tracks safer? A case–control study based on automated surrogate safety analysis using video data. *Accident Analysis & Preventio*n, 86, 161-172.
20) Nishiuchi, H., Shiomi, Y. & Todoroki, T. (2015). Segway running behavior focusing on riders' experience based on image-processing data. *Asian transport studies*, 3(4), 467-486.

(Received July, 2017)