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歩行者の安全・安心と交通円滑性を満たす自動運転車両の挙動要件に関する研究

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A study on the requirements of maneuver of automated vehicles to satisfy pedestrians' safety and traffic efficiency

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自動運転車両(AV)の本格的導入には，交通円滑性への影響を最小限にしつつ歩行者の安全性を担保することが重要である．本研究では単路部無信号横断歩道を対象に，ルールベースと強化学習を組み合わせたハイブリッド車両挙動モデルを提案し，遅れの増加を抑制しつつ，歩行者の予測困難な行動にも対応できることを示した．またバーチャルリアリティ歩行実験により，AV の危険行動が歩行者の危険な横断行動を誘発しうる危険性を示した．

For the implementation of automated vehicles, it is important to ensure the safety of pedestrians without having significant problems in terms of traffic efficiency. In this study, a hybrid model of vehicle maneuver was proposed by combining a rule-based model and a model with reinforcement learning, at unsignalized midblock crossings. It was shown that the model successfully reacted to unexpected maneuver of pedestrians with reducing vehicle delay. The possibility of risky pedestrian behavior triggered by hazardous AV maneuver was also shown via virtual-reality experiment.

1. 研究内容

1.1 Background and objective

In Japan, 70% of pedestrian-vehicle fatalities occur when pedestrians are crossing streets (National Police Agency, 2020). The unsignalized mid-block crosswalks (UMCs) are associated with safety risks for pedestrians. Meanwhile, the emergence of Autonomous Vehicles (AVs) could provoke unexpected challenges in the urban traffic environment, particularly on UMCs, where pedestrians are exposed to the AV flow. It is possible to apply discreet maneuver of AVs to ensure safety, while it may have great impact on efficiency of traffic. Additionally, it is important to understand pedestrian maneuver against AVs, since AVs need to make their motion plan taking into account the unexpected but possible reactions of pedestrians to them.

The aim of this research is to investigate the settings of autonomous vehicles which can satisfy both safety and efficiency. For that, we have proposed a novel agent-based framework of traffic simulation as well as a machine-learning algorithm of AVs. Furthermore, a virtual-reality experiment was conducted to understand the reaction of pedestrians toward such vehicles.

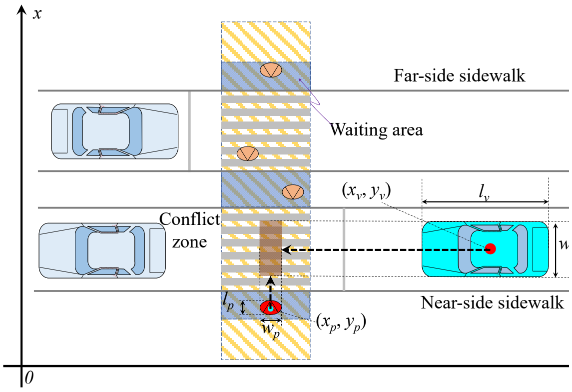
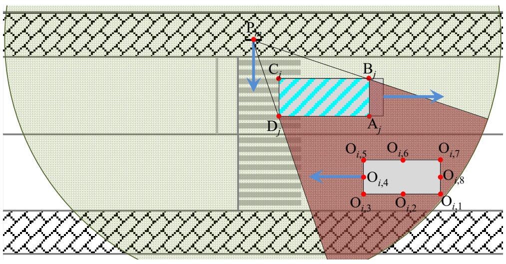
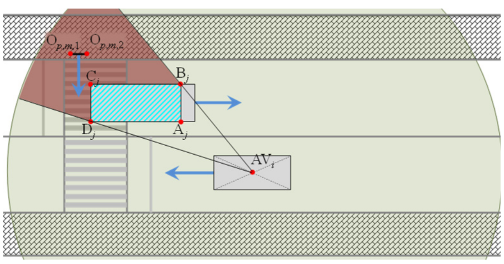


Figure 1. Two-dimensional coordinate system at a UMCR on a two-lane street



(a) Pedestrians' vision field



(b) Vehicles' vision field

Figure 2. Example visual field calculation in real scenarios

1.2 Agent-based traffic simulation for evaluation of detailed decision-making procedure

1.2.1 Model framework

The simulation framework is illustrated by taking a UMC with refuge islands (UMCRs) as an example as shown in Figure 1. The crosswalk is considered to be located within a two-dimensional coordinate system. Pedestrians are constrained to move vertically (y-direction), while the vehicles are constrained to move horizontally (x-direction). The conflict zone is the area enclosed by the extension lines corresponding to the boundaries of the approaching vehicle and the pedestrian. The blue areas are the waiting areas representing the place where pedestrians usually stand and wait before crossing. Both pedestrians and vehicles have visual ranges defined as a circle with the radius of sight distance. All visual obstacles and target objects are assumed to be rectangular shapes, and pedestrians and drivers can only detect obstacles within their visual ranges an in Figure 2.

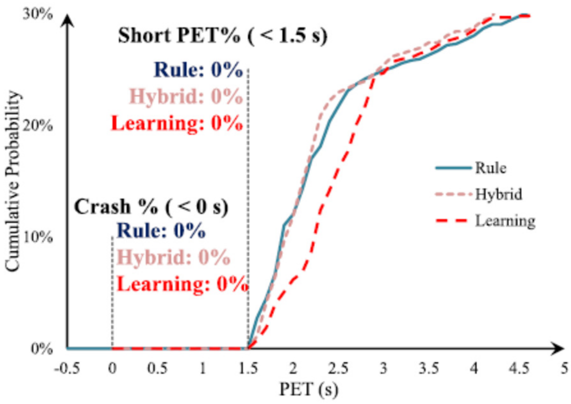
Pedestrian agents have perception, decision and walking behavior modules. In the decision models they judge whether they can complete crossing the conflict zone by keeping safety margin, forecasting behavior of approaching vehicles. Vehicle agents do the same, while there are 2 types of drivers assumed: 1 obeys the pedestrians' priority rule and the other try to compete with pedestrians over the right of way.

The simulation was validated using the empirical data videotaped in Inabachi-cho, Nagoya. Most of the parameters including reaction time of vehicles and pedestrians and deceleration rate are explicitly given from literature without tuning, the accuracy of the model in terms of Post Encroachment Time (PET), which is the surrogate safety measure, was considerably acceptable.

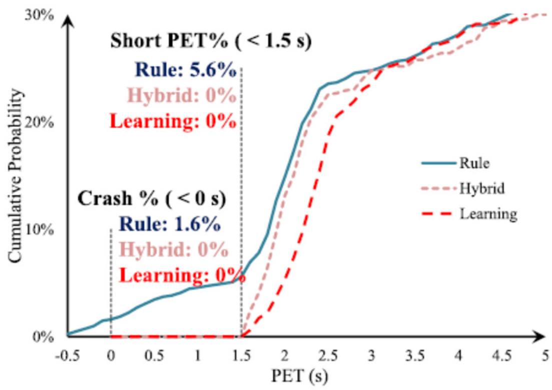
1.2.2 Machine-learning based optimization for efficiency and safety

Motion planning model was proposed considering the worst condition that pedestrians do not pay attention at all to drivers. Two new models are established for AVs: a rule-based model that solves motion plans through a fixed calculation procedure incorporating several optimization models, and a learning-based model that replaces the deterministic optimization process with policy-gradient reinforcement learning. In addition, a hybrid model was proposed as the third model in which rule-based acceleration value is introduced regularize the action space of the proposed learning-based model.

The developed models were assessed through simulation experiments in which pedestrian speed profiles were defined using empirical data from field surveys. Figure 3 shows PET distribution when vehicles face pedestrians with normal speed



(a) Scenario 1 (benchmark)



(b) Scenario 2 (Distraction + great speed difference)

Figure 3. PET distribution

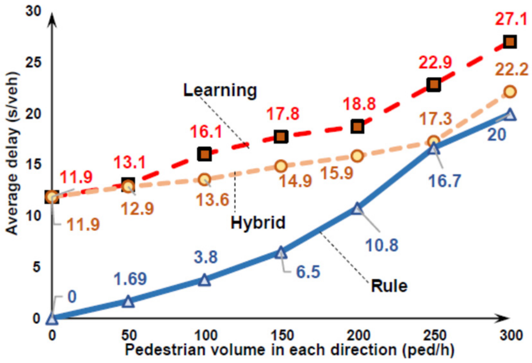


Figure 4. Average delay per vehicle

(Scenario 1) and those who are distracted and greatly change their speed while crossing (Scenario 2). The learning-based model has outstanding safety performance, whereas the rule-based model leads to remarkable safety problems. For distracted pedestrians with significant crossing-speed changes, rule-based AVs lead to a 5.1% probability of serious conflict and a 1.4% crash probability. Figure 4 investigates the delay of a single vehicle with different models. The vehicle volume is fixed as low as 50 veh/h for a given scenario in order to avoid the effect of vehicle accumulation on the experimental results. Settings of all pedestrians are those of Scenario 1. The rule-based model provides the least delay while the larger delay occurs even without pedestrians in learning-based model. The hybrid model takes advantages of both models, which successfully avoid short PETs and the delay do not unnecessary increase as the learning-based model.

1.3 Virtual Reality experiment for pedestrian' reaction

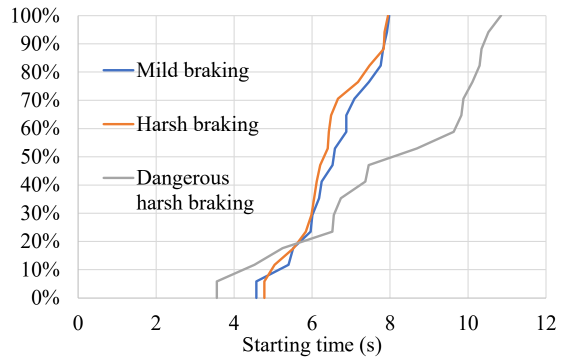
1.3.1 Settings

In the traffic simulation of the previous section, pedestrian motion was either assumed or generated based on the observed pedestrian profiles who face ordinary vehicles. However, pedestrians may react to AVs differently if the maneuver of AVs are different from those of ordinary human-driven vehicles. Therefore, a virtual-reality (VR) experiment was conducted to understand pedestrian behavior reacting to various types of approaching vehicle maneuver.

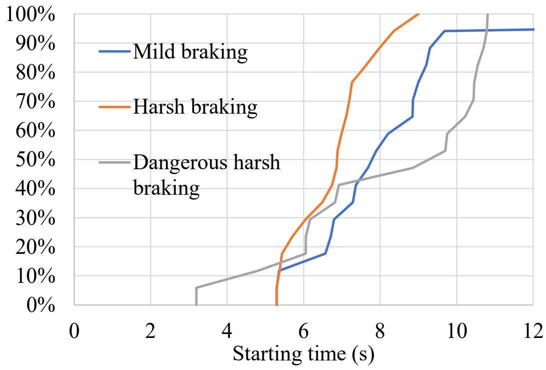
(a) VR view

(b) VR participant

Figure 5. VR environment



(a) 40km/h



(b) 60km/h

Figure 6. Distribution of pedestrian crossing start time

Forum 8 UC/Win-Road (Version 15.1) was utilized for building the VR environment and simulation. Participants wore head-mounted display (HTC VIVE Pro) and were asked to walk through a room (Figure 5). In the experiment, a two-way two-lane road is developed in the VR and the participant walk to cross an unsignalized crosswalk. 3 deceleration patterns of approaching vehicles are applied; mild braking, harsh braking and dangerous harsh braking. Mild braking is the case that vehicles start deceleration early enough to safety stop before the crosswalk. Harsh braking is that vehicles apply maximum deceleration rate and can stop in front of the crosswalk. Harsh dangerous braking also decelerates in maximum deceleration rate but cannot complete stopping before reaching the crosswalk. Initial speed of approaching vehicles are set as either 40 km/h and 60 km/h.

Participants start walking from 2m behind the crosswalk. The first few vehicles passes the crosswalk without deceleration and then the subject vehicle approaches with time gap of 3 seconds. The subject vehicle will take either of the deceleration patterns.

1.3.2 Results and findings

Figure 6. shows the distribution of the time when pedestrians start crossing after the last vehicle passes. Some participants facing dangerous harsh braking start earlier before the subject vehicle arrives. In a meantime, pedestrians facing harsh braking or mild braking carefully wait until the vehicles almost complete stopping. Since the dangerous harsh braking correspond to vehicles with the rule-based model which failed to stop in Section 1.2, it implies that the hazardous maneuver of rule-based model also triggers the hazardous maneuver of pedestrians.

1.4 Conclusions

This research introduced an agent-based pedestrian-vehicle interaction model for evaluating safety at unsignalized midblock crosswalks. The hybrid motion planning model of rule-based and learning-based models improved both surrogate safety measures and vehicle delays by adjusting approaching speed profiles to the crosswalk, while the rule-based model may have hazardous conditions that may have collisions. Furthermore, the VR experiment also revealed that the hazardous maneuver similar to the failure patterns of the rule-based model can cause the hazardous crossing maneuver of pedestrians.

In this study, the pedestrian maneuver is analyzed in the limited number of conditions in the VR experiment. As future works, it is necessary to analyze various other patterns, especially considering the variation of crosswalk geometries and other information provision systems for pedestrians to encourage safe crossings.

２．発表（研究成果の発表）

Zhu, H., Han, T., Alhajyaseen, W.K.M., Iryo-Asano, M. and Nakamura, H.: Can Automated Driving Prevent Crashes with Distracted Pedestrians? An Exploration of Motion Planning at Unsignalized Mid-block Crosswalks, Accident Analysis & Prevention, Vol.173, 106711, 2022.

Zhu, H., Iryo-Asano, M., Alhajyaseen, W.K.M., Nakamura, H. and Dias, C.: Interactions between Autonomous Vehicles and Pedestrians at Unsignalized Mid-block Crosswalks Considering Occlusions by Opposing Vehicles, Accident Analysis & Prevention, Vol. 163, 106468, 2021.