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Research article

Risk assessment based on driving behavior for preventing collisions with pedestrians when making across-traffic turns at intersections

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ABSTRACT

Traffic accident statistics in Japan show the necessity of preventing vehicle-on-pedestrian accidents. If the risk of a vehicle colliding with pedestrians could be evaluated in advance, driver-assistance systems would be able to support drivers to avoid potential collisions. Here, features of driving behavior and methods for assessing the risk of collision were investigated for a right turn at an intersection in left-hand traffic, which is a typical vehicle-on-pedestrian accident scenario. The results showed that pedestrian-collision risk can be evaluated from how the driver slows the vehicle and where the driver looks while turning during the maneuver. Moreover, pedestrian-collision risk could be predicted based on driving behavior upon commencement of steering when making an across-traffic turn.

1. Introduction

In Japan, traffic accidents involving vehicles hitting pedestrians who were crossing the road at the time accounted for the majority of fatal traffic accidents in 2015. Therefore, preventing traffic accidents involving pedestrians would lower the number of fatalities. As a means to prevent conflicts between pedestrians and vehicles, warning and automatic braking systems have been developed [1–5]. However, because these systems are designed to activate only upon detecting pedestrians, they are ineffective if the pedestrians are somehow obstructed from view, such as cases where vehicles are turning and cases where pedestrians are masked by obstacles [6]. However, if the risk of colliding with pedestrians could be evaluated in advance based on driving behavior without waiting detection of pedestrians, driver-assistance systems would be able to support the driver in driving properly to avoid colliding with crossing pedestrians.

Driving a vehicle is an adaptive operation in which the driver behaves preemptively (e.g., adjusting vehicle speed, adjusting safety margins) to avoid colliding with stationary objects and other road users. This preemptive behavior is based on the driver's anticipated and perceived risk from the traffic environment. Van der Hulst et al. [7] showed in a car-following scenario that drivers take longer time-headways between themselves and the car in front if they were able to anticipate deceleration of the preceding vehicle. Such drivers were able to maintain a safer distance (i.e., a lower risk of collision) compared to drivers who did not expect the preceding vehicle to brake suddenly. Thus, there is a lower risk of collision if drivers behave on the basis of sufficient anticipation of risks in their surroundings. If features of driving behavior associated with a low risk of collision (or indeed a high risk) were known, the risk of collision could be evaluated by comparing the present measured behavior with those behavioral features.

The aim of the present study is to demonstrate that the risk of vehicle-on-pedestrian collision can be evaluated from features of driving behavior. To achieve this aim, we investigated driving-behavior features and associated methods that are valid for assessing vehicle-on-pedestrian collision risk before a typical risk scenario is encountered. From the perspective of executing driver assistance to avoid collision, it is important to know how and when collision risk can be evaluated based on measured driving behavior. Thus, this research consists of two parts. In the first part, we hypothesized which features of driving behavior indicate a risk of vehicle-on-pedestrian collision. Then, to determine whether collision risk can be evaluated, we assessed those hypotheses in experiments designed to reproduce a risky scenario using a real vehicle on a test course. In the second part, to address the question of when to evaluate collision risk, we predicted an impending collision by using the experimental data from the first part.

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2. Target driving scenario

Right turns at intersections (in left-hand traffic) represent a considerable safety problem for pedestrians in Japan [8,9], as in other countries [10,11] (where it is mostly left turns in right-hand traffic). During right turns in left-hand traffic (left turns in right-hand traffic), the mental workload of the driver is larger compared to other maneuvers at intersections [12]. The driver is required to pay attention to many aspects simultaneously, such as oncoming vehicles and pedestrians, because the host-vehicle path crosses those of oncoming vehicles and of pedestrians [13]. Because of this characteristic, the importance of risk anticipation toward the environment for behavioral selection in right turns is suggested to be higher than in other driving scenarios. For this reason, the driving behavior associated with right turns is likely to be more reflective of anticipated collision risk than in other driving scenarios. Therefore, we selected right turns at intersections as the target driving scenario in this study.

Shino et al. [14] clarified the environmental elements that affect the driving behavior associated with right turns at signalized intersections using the near-miss incident database collected and owned by the Japanese Society of Automotive Engineers (JSAE) [15]. Moreover, they classified 10 typical scenarios of right turns at signalized intersections with crossing pedestrians based on those clarified environmental elements. Among the classified typical right-turn scenarios, to exclude the influence of other road users (e.g., preceding vehicles and oncoming vehicles) on driving behavior and pedestrian-collision risk, we chose the right turn with no other road users other than a crossing pedestrian as the target right-turn scenario in the present study, as shown in Fig. 1.

3. Driving-behavior features indicating pedestrian-collision risk

3.1. Hypothesis and index definition

We hypothesized the relevant driving behavioral features by considering the normative behavior of a driver making a right turn at an intersection while anticipating that a crossing pedestrian might appear at the crosswalk. We assumed that a driver who is aware of a crossing pedestrian in a right-turn situation will drive in a way that allows a sufficient margin of safety between the host vehicle and pedestrian to avoid a collision. To do so, the driver needs to spot the pedestrian as soon as possible. Researches on “looked-but-failed-to-see” errors, which lead to latent detection of critical targets (e.g., bicycles, pedestrians), reveal that failure in drivers' visual search strategy is one of the major causes of the errors [16,17]. Summala et al. [18] state that speed modifies visual scanning patterns of drivers and slower speed simply gives them more time to look around. Considering facts from the studies, there are two possible strategies. One is to drive slowly enough to allow enough time to spot the pedestrian. The other is to look in the appropriate direction to avoid not seeing the pedestrian. Thus, we chose to focus on “adjustment of vehicle speed” and “distribution of visual attention” as driving behavioral features that may indicate pedestrian-collision risk. Each behavioral feature is assumed to affect time margin and response time for pedestrian detection respectively.

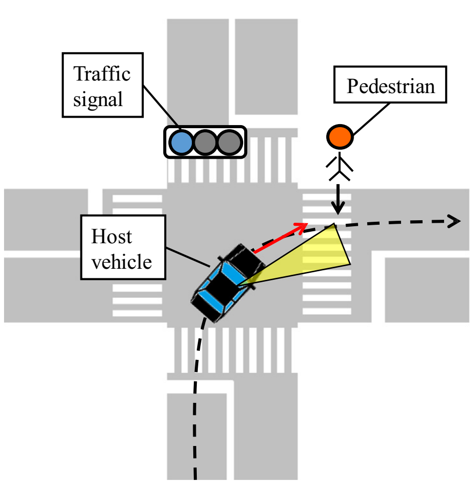

Fig. 1. Overhead view of target driving scenario: a right turn at a signalized intersection in left-hand traffic with no other road users other than a pedestrian walking toward/on the crosswalk.

We defined two driving behavioral indices of pedestrian-collision risk based on the hypotheses under two assumptions. One is that drivers steer toward a target destination near the crosswalk during right turns at intersections. The other is that the collision risk is reflected in the driving behavior at the road centerline, namely the boundary between the driver's lane and the oncoming lane. To make a right turn, the driver must cross the centerline and enter the oncoming lane. Thus, it could be said that crossing the centerline is a representative timing of a right-turn maneuver reflecting drivers' decision-making.

As an index related to the “adjustment of vehicle speed” feature, we defined the vehicle speed at the centerline as V_{cl}. For the index related to the “distribution of visual attention” feature, we considered characteristics of driver attention allocation. Summala et al. [19] investigated the visual scanning behavior of drivers at T-junctions and reported a developed scanning strategy that is concentrated on detecting frequent and critical hazards (e.g., crossing vehicles) at the expense of less frequent hazards (e.g., bicycles). By applying the attention-selection modes introduced by Trick et al. [20], the selection strategy of the driver can be rephrased as one that concentrates more on habitual attention and less on deliberate attention. This type of scanning strategy is assumed to lead to failures to spot cyclists and pedestrians because those represent less frequent and arguably less critical hazards. In the right-turn scenario being considered here, given the nature of vehicle control, we assume that habitual attention is paid to the direction in which the driver expects to be traveling in the near future (the turning direction), because various researches show that drivers tend to look toward a tangent point of the future path for steering [21,22]. In contrast, in relation to deliberate attention, it is necessary to distribute attention toward the crosswalk and its ends, which are distant from the turning direction, to spot pedestrians and so avoid colliding with them. Thus, visual attention directed toward the turning direction is a promising feature for indicating collision risk in the target scenario. Results from Shino et al. [14] of analyzing near-miss incidents showed that the drivers involved in such incidents tended to spend a long time facing toward the turning direction, supporting this assumption.

Although the face/gaze direction is measurable using on-board cameras, it is difficult in a relative coordinate system to determine whether it corresponds to the turning direction. Hence, we defined an alternative index considering the behavior of the driver. When a person operates a vehicle, it is widely believed that they plan for a desired trajectory and maneuver accordingly. Supporting this assumption, certain driving-behavior models for lateral control consider the drivers' preview behavior toward the potential trajectory [23,24]. From these models, the angle between the drivers' gaze direction along the potential trajectory and the vehicle front direction is assumed to increase with the curvature, and drivers are expected to look more toward the turning direction as shown in Fig. 2. This will possibly lead to visual attention being paid longer toward the turning direction away from the crosswalk ends. Therefore, we defined a curvature index based on the present position on the centerline and the target destination with the following equation:

$$\varphi_{cl} = \frac{\theta_{dst}}{D_{dst} - FL_{hv}}, \tag{1}$$

where θ_{dst} denotes the angular deviation between the target destination and the host vehicle's COG, D_{dst} denotes the distance between the target destination and the host vehicle's COG, and FL_{hv} denotes the front

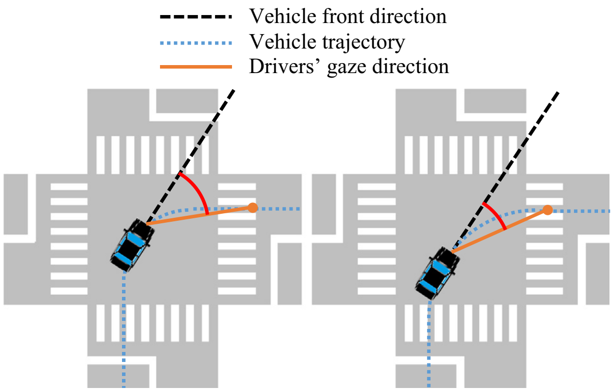

Fig. 2. Relationship between trajectory curvature and drivers' gaze direction: large curvature (left); small curvature (right).

vehicle length from the COG of the host vehicle as shown in Fig. 3. This index represents the change in vehicle angle per unit distance from the centerline to the target destination.

3.2. Method

We examined the validity of the defined indices by experimentally reproducing driving scenarios including a scenario in which a crossing pedestrian appears at the crosswalk, where collisions between the pedestrian and the host vehicle driven by a test participant may occur. In addition, reference measures were defined for examination.

3.2.1. Experiment conditions

The JARI-ARV (augmented-reality vehicle) [25] owned by the Japan Automobile Research Institute (JARI) was used to reproduce risk scenarios without putting real pedestrians in danger. This vehicle has video cameras and displays on its hood, and the driver can operate the vehicle by viewing the surroundings through the displays, that cover almost a 110-degree horizontal field of view, in the form of the images acquired by the video cameras and processed by a workstation installed in the vehicle's cargo space. These features allow this vehicle to be used to reproduce risk scenarios by superimposing computer graphic (CG) objects on real frontal images of scheduled events, as shown in Fig. 4. This augmented-reality technology gives the driver the impression that pedestrians and other vehicles actually exist in the test field, thereby enabling risk-scenario experiments with a real vehicle. In comparison with conventional driving simulators, the advantage of this test vehicle with a mixture of real and simulated environment is high reproducibility in virtual driving simulation compatible with realism in driving with actual motion and haptic feedback.

Two scenarios were reproduced using CG objects at an intersection with two lanes on each side and a traffic signal inside a test field: the non-pedestrian (NP) scenario in which no crossing pedestrian appears at the crosswalk, and the with-pedestrian (WP) scenario in which a pedestrian appears at the crosswalk. To reproduce the target driving scenario, no other road users besides the crossing pedestrian existed near the intersection during a right turn. If there were no road users near the intersection, a driver may not anticipate the existence of a crossing pedestrian at all and the driving behavior may deviate from that on public roads. Therefore, walls were set at the corners of the intersection to restrict visibility of the intersection and present possibility that an invisible pedestrian may start crossing from behind it. Details of the scenarios reproduced are shown in Fig. 5. A CG oncoming vehicle passes by the host vehicle before it reaches the stop line in both scenarios. This oncoming vehicle was included for the same purpose with the walls. For the WP scenario, a CG pedestrian starts walking from behind the wall when the host vehicle reaches the centerline. We made the CG pedestrian to appear at this timing to make it easier to reproduce a critical scene by making the pedestrian appear suddenly after the driver started to turn right. Each driver drove through the target intersection eight times in a specific order: twice to practice vehicle operation without any CG scenarios, twice to practice the NP scenario, three times to drive the NP scenario, and once to drive the WP scenario. The last four right turns at the intersection were the analysis target. The drivers were instructed to drive as they usually do and keep in mind that the speed limit is 40 km/h. The vehicle behavior (e.g., vehicle position, velocity, acceleration), driver operation (e.g., pedal operation, steering-wheel operation), and camera images (e.g., front camera, driver face camera) were recorded by a data recorder installed on the JARI-ARV. The gaze behavior of each participant was measured with a wearable eye-tracking system (EMR-9; NAC Image Technology, Inc.). The eye-tracking system was mounted, and a calibration was carried out before the experiment for each participant. The participants were 26 people (D01–D26; average age 32.6 years (SD = 6.6 years); 15 men and 11 women) who possessed a valid driving license and drove on a daily basis. The participants were briefed thoroughly about the nature of the experiment, and informed consent was obtained from each person before the experiment. This experiment was carried out under the approval of the ethics committee of the University of Tokyo.

3.2.2. Reference measures

Proposed driving behavior index φ_{cl} was assumed to have relation with drivers' gaze direction. To validate the relationship, we defined the gaze direction angle (*GDA*) as shown in Fig. 6 where counterclockwise direction is positive, and a reference measure GDA_{avg}. GDA_{avg} is the average *GDA* of the period from the time the vehicle passed the centerline to the time it reached the crosswalk. Right-turn driving behavior with smaller GDA_{avg} indicates that the driver was looking more toward the turning direction. We evaluated the relationship between GDA_{avg} and φ_{cl} of the NP scenario to assess the validity of φ_{cl} as an index representing drivers' gaze behavior.

The two driving behavior indices were assumed to be related to time margin for pedestrian detection and response time of pedestrian detection respectively. Therefore, we quantified both the time margin and response time for examination. The time margin for pedestrian detection (*TM*) was quantified as the driving time from the centerline to the crosswalk of the NP scenario. The response time for pedestrian detection (*RT*) was quantified as the braking response time of the driver in response to the crossing pedestrian appearing from behind the wall of the WP scenario. The relationship between the driving behavior indices were examined respectively.

To assess the validity of the proposed driving-behavior indices as a pedestrian-collision risk index, we defined a reference measure TTC_{brake} for pedestrian-collision risk with a virtual conflict point at which the po-

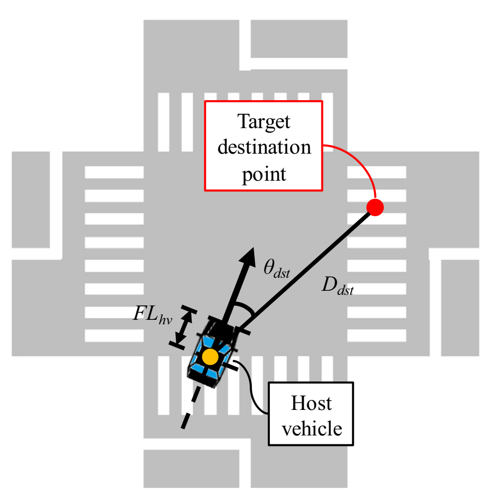

Fig. 3. Description of parameters for φ_{cl} definition.

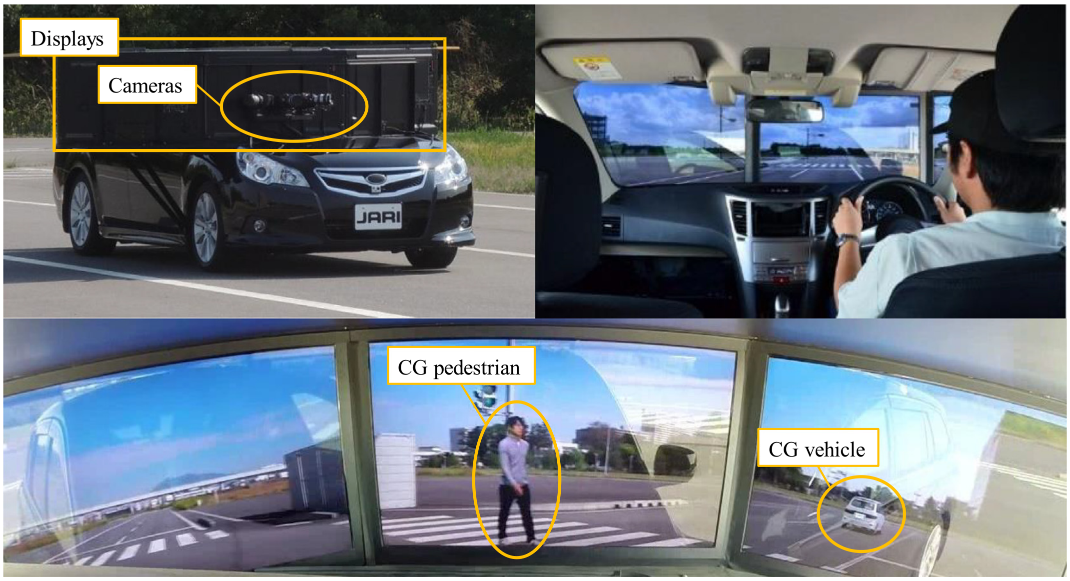

Fig. 4. Augmented-reality vehicle JARI-ARV (top-left: outer view of JARI-ARV; top-right: inner view of JARI-ARV; bottom: real front-window image with superimposed CG objects).

tential trajectories of the host vehicle and crossing pedestrian overlap. Measure TTC_{brake} is the time-to-collision value between the host vehicle and crossing pedestrian calculated with the driving behavior of the driver's braking maneuver timing, and is given by.

$$TTC_{brake} = \frac{D_{cp} - FL_{hv}}{V_{hv} cos\theta_{cp}}, \quad (2)$$

where D_{cp} denotes the distance between the virtual conflict point and the host vehicle's COG, FL_{hv} denotes the front vehicle length from the COG of the host vehicle to its front end, V_{hv} denotes the host vehicle's speed, and θ_{cp} denotes the angular deviation between the virtual conflict point and the host vehicle's COG. We evaluated the relationship between TTC_{brake} and the driving-behavior indices of the WP scenario to assess the validity of the indices and the feature hypotheses.

3.3. Results

3.3.1. Drivers' avoidance behavior against crossing pedestrian

With regard to the avoidance behavior of the participants toward the crossing pedestrian who appeared in the WP scenario, four participants did not press the brake pedal even though they noticed the crossing pedestrian, and one participant was already pressing the brake pedal when he spotted the crossing pedestrian. Therefore, the reference measure TTC_{brake} could not be calculated for those five participants. Fig. 7 shows the relationship between TTC_{brake} and the maximum braking deceleration in response to the crossing pedestrian for those drivers who stopped or decelerated in front of the pedestrian ($N = 15$). Deceleration against the crossing pedestrian less than the threshold for start recording near-miss incidents (0.45 g) applied in the JSAE near-miss incident database [26] indicates that the braking was of a non-emergency nature and the driving behavior before encountering the crossing

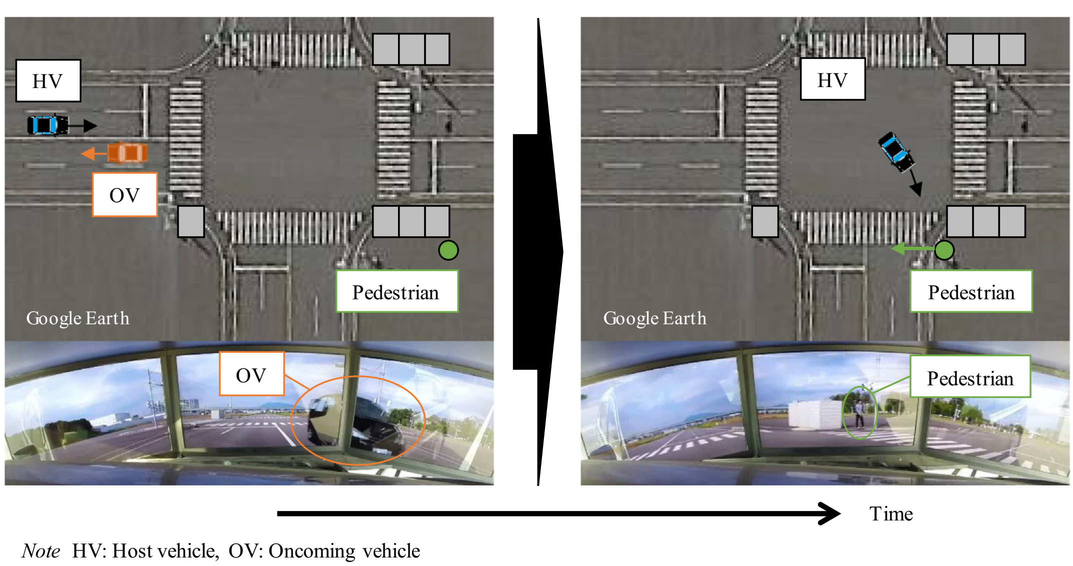

Fig. 5. Description of experimental scenario (top: overhead view; bottom: actual front-window image of the JARI-ARV with superimposed CG objects).

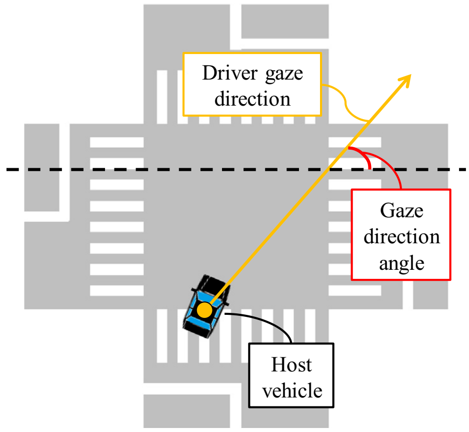

Fig. 6. Definition of *GDA*.

pedestrian was low-risk and enabled the driver to avoid collision without any hard braking. From the results, we considered that driving behavior for which TTC_{brake} exceeds 2.0 s is relatively low-risk because the associated decelerations were all less than the near-miss incident threshold.

3.3.2. Relationship between driving-behavior indices and reference measures

As hypothesized in Section 3.1, the driving-behavior index φ_{cl} is likely related to the direction where the visual attention is paid. Experiment results revealed that there was significant correlation between φ_{cl} and GDA_{avg} for the NP-scenario data ($r = -0.44$, $t(71) = -2.21$, $p < 0.01$). This shows that the driving-behavior index φ_{cl} represents the drivers' gaze direction.

The two driving behavior indices were assumed to be related to time margin for pedestrian detection and response time of pedestrian detection respectively. There was significant correlation between V_{cl} and *TM* for the NP-scenario data ($r = -0.85$, $t(74) = -13.91$, $p < 0.01$). This result confirms that the "adjustment of vehicle speed" feature affects the time margin for pedestrian detection. As for φ_{cl}, this index correlated significantly with *RT* for the WP-scenario data ($r = 0.78$, $t(19) = 5.39$, $p < 0.01$). This reveals that a right turn with a smaller value of φ_{cl} enables the driver to detect the crossing pedestrian sooner in the target scenario.

Fig. 8 shows the relationships between TTC_{brake} and the two driving-behavior indices. As can be seen, there is no significant correlation between the reference measure and either driving-behavior index (φ_{cl}: $r = -0.26$, $t(19) = -1.20$, $p = 0.25 > 0.05$; V_{cl}: $r = -0.31$, $t(19) = -1.47$, $p = 0.16 > 0.05$). There were cases with large φ_{cl} and relatively long TTC_{brake}, although TTC_{brake} was expected to be long when φ_{cl} was small. Also, low V_{cl} was assumed to be the behavior with a low collision risk, but there were cases with relatively short TTC_{brake} values. These instances indicate that the two indices partially represent the risk of colliding with crossing pedestrians, but not sufficiently so for collision-risk evaluation individually.

Although neither index showed significant correlation with pedestrian-collision risk, the tendency suggests that the two indices may compensate for each other. Fig. 9 shows φ_{cl} and V_{cl} as a pair classified into three risk levels according to TTC_{brake}. As shown in Fig. 9, the data plots of the different risk levels can be distinguished visually. Thus, pedestrian-collision risk could possibly be evaluated using the two driving-behavior indices. We conducted a multivariate linear regression analysis to examine the relationship between the risk

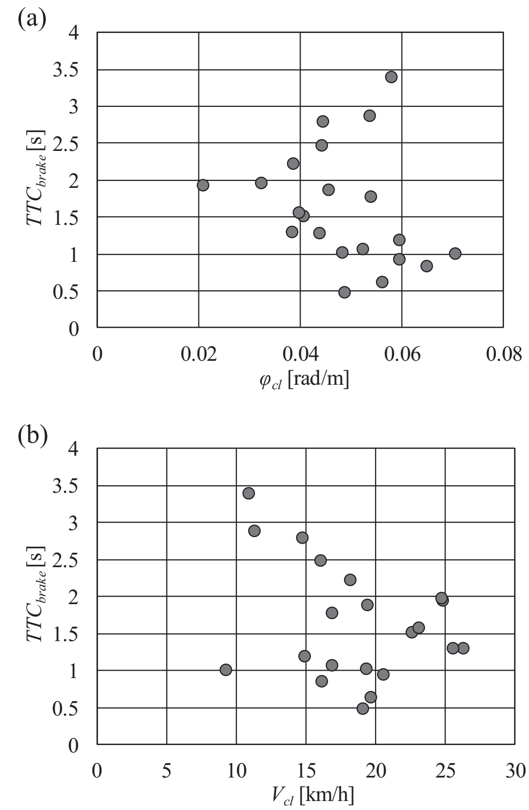

Fig. 8. Relationships between TTC_{brake} and driving-behavior indices (φ_{cl} and V_{cl}). (a) φ_{cl} vs. TTC_{brake}, (b) V_{cl} vs. TTC_{brake}.

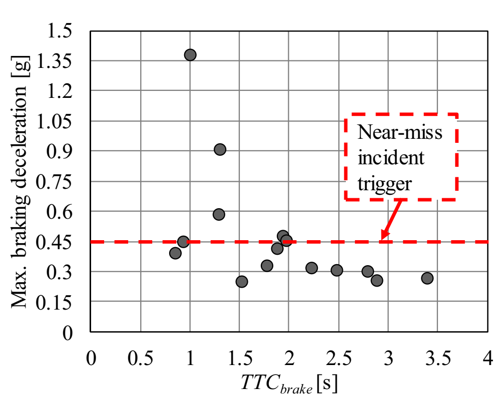

Fig. 7. Relationship between TTC_{brake} and maximum braking deceleration in response to crossing pedestrian for those drivers who either stopped or decelerated in front of the pedestrian.

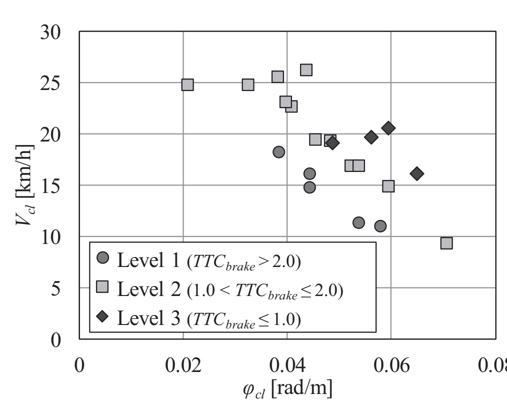

Fig. 9. Relationship between paired driving-behavior indices (φ_{cl} and V_{cl}) and risk levels of driving behavior.

Table 1
Summary of multivariate linear regression analysis for variables predicting TTC_{brake}.

Variable	B	SE	t
(Constant)	8.18	1.25	6.56**
φ_{cl}	−69.95	14.52	−4.82**
V_{cl}	−0.17	0.03	−4.97**
R^2		0.61	
F		13.9**	
N		21	

** $p < 0.01$.

reference TTC_{brake} and the two driving-behavior indices. Table 1 shows the summary of the analysis. As can be seen in Table 1, the driving-behavior indices had significant negative regression weights, although they did not have significant correlation between the reference measure individually. This result indicates that φ_{cl} and V_{cl} together, they are efficient parameters for assessing pedestrian-collision risk, and that such risk can be evaluated based on the two driving-behavior features hypothesized in Section 3.1. As shown previously, the two indices are related to time-dimension factors that affect driver detection of crossing pedestrians (time margin and response time). Hence, the pedestrian-collision risk, which is assumed to be an index of time dimension, can be evaluated based on the defined indices.

4. Investigation of predicting pedestrian-collision risk

4.1. Method

As an approach to assessing the possibility of predicting pedestrian-collision risk before crossing the centerline (i.e., entering the opposite lane), we performed two-step classification of driver behavior before reaching the centerline as either high- or low-risk driving behavior. Firstly, the driving-behavior indices (φ_{cl} and V_{cl}) at the centerline were estimated using a multivariate linear regression model with the driving behavior at a certain driving event before reaching the centerline as its variables. Secondly, the estimated driving behavior at the centerline was classified as either high- or low-risk driving behavior using a linear discriminant model with φ_{cl} and V_{cl} as its variables.

4.1.1. Multivariate regression model

The estimation event must be an event that occurs before the driver reaches the centerline. Of the events shown in Fig. 10 that meet this requirement, we focused on braking start (BS), steering start (SS), and stop-line pass (SP). These events were selected on the basis that BS and SS are under driver control events, and SP corresponds to the vehicle entering the intersection. We defined the time of an SS event as the time at which the steering-wheel angle first exceeds 30°. For the explanatory variables, we used distance to the center of the intersection, the vehicle speed, and the longitudinal acceleration; these were selected because the driving behavior before reaching the centerline mostly involves driving in a straight line with no lateral control. The training data of the model were the experimental data obtained in the previous section, and we identified the model with the minimum AIC (Akaike information criterion).

4.1.2. Discriminant model

The model consists of φ_{cl} and V_{cl} to distinguish between high-risk behavior ($TTC_{brake} \le 2.0$ s) and low-risk behavior ($TTC_{brake} > 2.0$ s). The TTC_{brake} threshold of 2.0 s for classification of high- and low-risk driving behavior was obtained from the investigation results of Section 3.3.1. The training data were the WP-scenario data of the JARI-ARV experiment. The model was formulated with the driving behavior at the centerline.

4.2. Results

4.2.1. Estimation of driving-behavior indices

Fig. 11 shows the adjusted coefficient of determination (R^2_{adj}) of the multivariate regression model for each estimation event with the minimum AIC. The regression model of the SS event had an R^2_{adj} value of

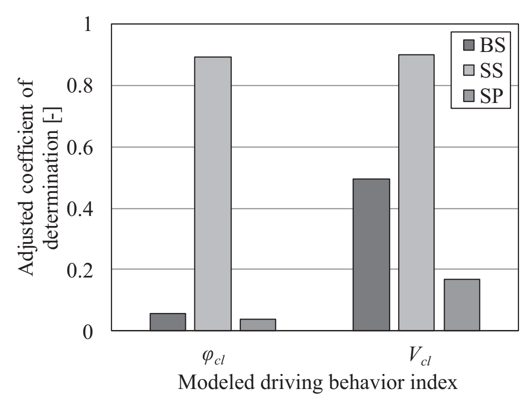

Fig. 11. Adjusted coefficient of determination of multivariate regression models (φ_{cl} & V_{cl}) using driving behavior of three estimation events.

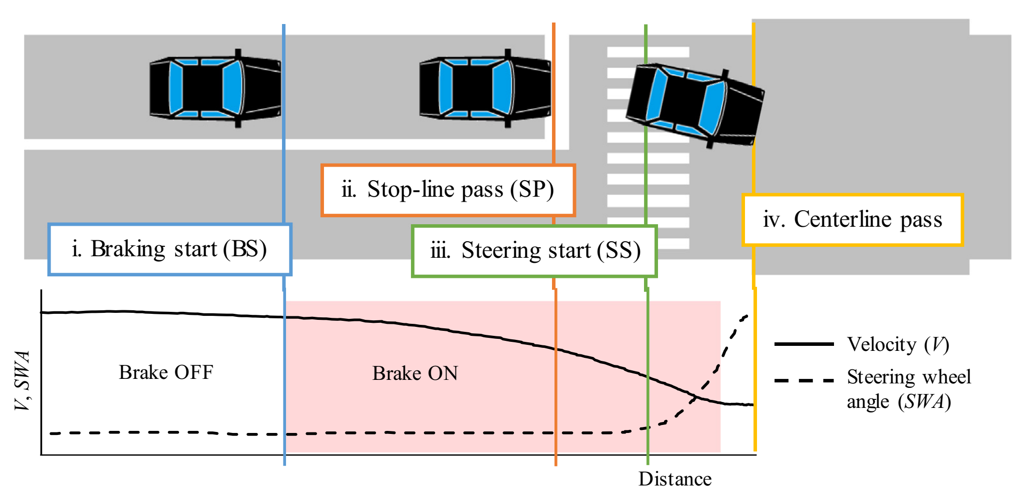

Fig. 10. Driving events before reaching the centerline in a right-turn maneuver at an intersection.

approximately 0.9, which is a relatively high value. For the other estimation events, R^2_{adj} did not exceed 0.4, showing that it could not sufficiently formulate the driving behavior at the centerline using the driving behavior data of the BS and SP events. Therefore, it was clarified that the SS event is valid for estimating the driving-behavior indices at the centerline.

4.2.2. Discrimination of high- and low-risk driving behavior

Fig. 12 shows the estimated pair of φ_{cl} and V_{cl} based on the regression model formulated previously using the driving behavior data at the SS event, as well as the discriminant line so modeled. The discriminant rate was over 85% with high discrimination accuracy. This indicates that the risk associated with driver behavior when encountering a crossing pedestrian during a right turn at an intersection can be predicted based on the driving behavior at the SS event.

Under these experimental conditions, discrimination of driving behavior was available on average 1.28 s (SD = 0.29 s) before reaching the centerline. Compared to the average driving time between centerline and crosswalk (2.76 s; SD = 0.47 s), the time available for driver-assistance judgment and execution could be extended by approximately 50% by predicting pedestrian-collision risk based on estimated driving behavior at the commencement of steering.

5. Discussion

From the results given in Section 4.2, we deem the SS event to be a meaningful operational event for the driver. The commencement of steering means that the driver starts to orient the vehicle toward a right-turn destination, which is an operation that cannot be undertaken if no destination target is planned. Therefore, we assume that the driver has a definite target in mind upon commencing steering; this is possibly the reason why the driving behavior at that time was effective for predicting subsequent driving behavior. In contrast, neither the BS nor the SP event was effective. For the SP event, the drivers might have used the stop line as a way to notice their vehicle position and determine their next operation. However, the results showed that the drivers were not determining their behavior with respect to the stop line. As for the BS event, because it corresponds to the drivers' braking operation, it was assumed to have relation with future behavior similar to the SS event. The purpose of this braking maneuver is to slow the vehicle before it reaches the intersection. Braking is also necessary when making a right turn, but it seems to be a more habitual operation with an obscure target than with a clear one. Fig. 13 shows the statistics of multivariate regression models of the speed at the stop line and centerline modeled with the driving behavior of the BS event as explanatory variables. This result shows that R^2_{adj} value of the stop-line speed is higher than that of the center-line speed, indicating that drivers tend to start to brake and slow their vehicles in response more to the existence of the intersection rather than because of the right-turn maneuver that they are about to make.

The discrimination of driving behavior in Section 4.2.2 showed the possibility of executing driver assistance based on the driving behavior at the commencement of steering in a right-turn maneuver. However, as shown in Fig. 12, three drivers received false-negative discrimination; they were classed as low risk when in fact their driving behavior was high-risk. In such false-negative cases, driver assistance could not be executed at the commencement of steering with the methods proposed here. As a characteristic of such cases, the driving behavior of the three drivers is suggested to become more “risky” as they approach the centerline, and consequently deviates from the estimated driving behavior. The results of this study show that it would be possible to construct a continuous driving-behavior model for the period between commencing steering and passing the centerline because the behavior at the centerline can be predicted from that upon commencement of steering. If such a continuous behavior model was constructed, right-turn driving behavior would be distinguishable not only at certain events (e.g., commencement of steering) but at various times by observing the deviation between the desired and measured behavior. We expect this to reduce false discrimination of right-turn driving behavior.

A limitation of this study is the relatively small sample size. For this reason, the findings in this study cannot be generalized based on this study alone. Another limitation is the limited experimental conditions of the driving scenario. The experiment was conducted in an environment where no other traffic participant exists and therefore findings of this research are limited to the scope of this elementary right-turn driving scenario. However, this simple right-turn scenario is considered to be the basis of other right-turn scenarios and there is possibility that the outcomes of this study can be applied to more complex scenarios.

The evaluation method of pedestrian-collision risk while turning right at intersections considered in this study focused on two driving behavior features, “adjustment of vehicle speed” and “distribution of visual attention”. As described above, it is suggested that risk assessment was possible because “adjustment of vehicle speed” and “distribution of visual attention” were related to the accident factors respectively, time margin and response time of pedestrian detection. In other driving scenarios such as left turns at intersections, it is assumed that the accident factors of vehicle-on-pedestrian accidents are fundamentally the same with turning right at intersections. Therefore, there is possibility that the methodology examined in this study can be applied to other driving scenarios with different driving-behavior indices suitable for the driving scenario.

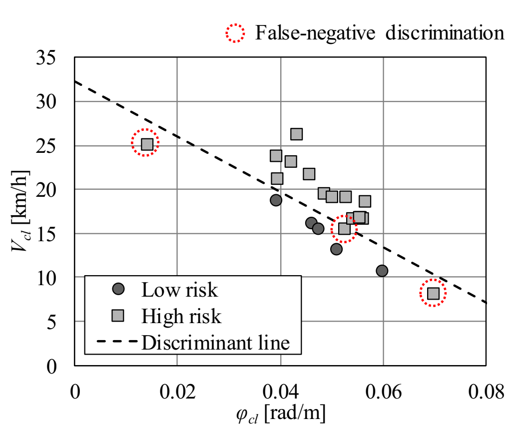

Fig. 12. Discrimination results of high- and low-risk driving behavior based on driving behavior at the commencement of steering.

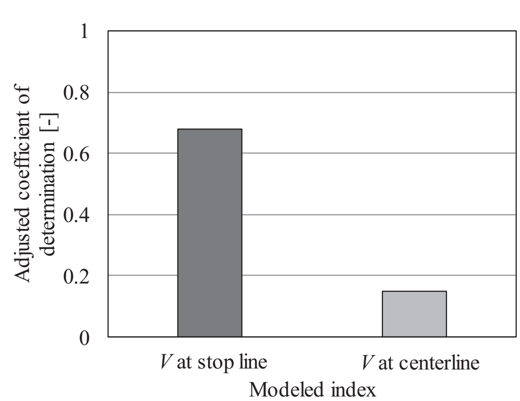

Fig. 13. Adjusted coefficient of determination of multivariate regression models (speed at stop line and centerline) using driving behavior of BS event.

6. Conclusions

To discover features of driving behavior that could be used to assess the risk of a car colliding with crossing pedestrians while turning right at an intersection, we firstly hypothesized driving-behavior indices based on assumed driver behavior related to anticipating pedestrian appearance. Next, we examined the hypothesized indices with a risk-scenario-reproducing experiment using the JARI-ARV. Finally, we examined the possibility of predicting driving behavior with high or low risk of pedestrian collision based on the behavior before reaching the centerline using the JARI-ARV experimental data. The followings are our conclusions from this study.

- The risk of a car colliding with crossing pedestrians while turning right at an intersection can be evaluated by focusing on the "adjustment of vehicle speed" behavior represented by V_{cl} and the "distribution of visual attention" behavior represented by φ_{cl}.
- The driving behavior at the centerline while turning right can be estimated from the driving behavior at the commencement of steering by using a multivariate linear regression model. In contrast, the driving behavior upon commencing braking or passing the stop line is ineffective for predicting subsequent behavior.
- It is possible to classify driving behavior while turning right as either high or low risk with regard to pedestrian collision by using a linear discriminant model based on driving behavior estimated at the commencement of steering.

In the future, we plan to design and evaluate driver-assistance methods considering the results of the present study. In addition, we plan to examine the influence of other elements of the traffic environment (e.g., road geometry, existence of other road users) on the driving-behavior features to extend the range of applications of the results of the present study.

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