AN EVALUATION PROTOCOL FOR COLLISION AVOIDANCE AND MITIGATION SYSTEMS AND ITS APPLICATION TO SAFETY ESTIMATION

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ABSTRACT

After a decade of reductions in passenger fatalities by improving vehicle crash safety, pedestrians now account for the majority of traffic accident fatalities in Japan. Collision Avoidance and Mitigation Systems (CAMS) are intended to monitor objects ahead including pedestrians, issue a warning to the driver upon detecting an object, and activate automatic brakes. CAMS are promising technologies for reducing pedestrian and motor vehicle accidents. However, there are currently no standardized test methods for evaluating their safety performance and they have been slow to spread in the market. This study proposes a protocol for evaluating the performance of CAMS, and estimates their effect on reducing pedestrian fatalities and injuries.

We used two test vehicles with CAMS having different sensing systems. To investigate the collision avoidance performance of CAMS, a test vehicle was driven toward a pedestrian dummy which was set up on a test course, and the collision avoidance situations were recorded. Among various test conditions, daytime, dry road surface, side-facing pedestrian, black clothing (pedestrian), and center position (of the vehicle) were selected as standard test conditions.

In evaluating the performance of CAMS, we used the criterion of whether or not a collision with the pedestrian dummy was avoided without any operation by the driver. The results showed substantial variability in collision and avoidance even under the same standard conditions. In order to include the uncertainty of the collision avoidance results, we assumed collisions to be probabilistic events. By applying a logistic regression model with "p" as the probability of pedestrian dummy collision and vehicle speed "x" as an explanatory variable when using CAMS under the standard conditions, we defined collision probability "p(x)" as the performance of CAMS. p(x) clearly shows the differences in performance between two vehicles tested.

We analyzed factors contributing to the differences in performance. As the two main functions of CAMS are to detect pedestrians and to apply the automatic brakes, we used the warning timing as a measurement of the detection function, and the braking timing as a measurement of the automatic brake function. An analysis of the difference in collision avoidance performance between the two vehicle models showed that the timing of automatic brake activation is the cause of the difference. It was also found that in order to increase the collision avoidance probability, it is more effective to activate the automatic brake based on CAMS' judgment, rather than to wait for the driver to respond to a warning.

In the traffic fatality and injury data, we estimated the fatality reduction effect of CAMS by applying the defined accident avoidance probability of CAMS. Due to the performance of CAMS, the effect on reducing pedestrian fatalities is larger at low and medium speeds. CAMS also have a more significant effect on reducing severe injuries because the rate of severe injuries is higher at low and medium speeds where the CAMS collision avoidance probability is higher.

INTRODUCTION

The number of traffic fatalities in Japan has steadily decreased and reached a record low of 4,411 in 2012, even though the figure is still well over 4,000. However, pedestrian fatalities have relatively increased and have accounted for the largest proportion of traffic fatalities since 2008, overtaking vehicle driver and occupant fatalities.

The Japanese government's Ninth Fundamental Traffic Safety Program, which was drafted in March 2011, set the goal of reducing the number of 24-hour fatalities (deaths within 24 hours after an accident) to 3,000 or less by 2015 in order to make the country's roads the safest in the world. In addition, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) proposed a numerical target of reducing traffic fatalities by approximately 1,000 by 2020 compared to 2010 by means of vehicle safety measures. In order to achieve this target, it is essential to develop and encourage the use of various safety technologies.

Collision Avoidance and Mitigation Systems (CAMS) are designed to monitor objects ahead including pedestrians, issue a warning to the driver if an object is detected, and activate automatic brakes if the driver

does not take action. The conventional systems are designed to mitigate damage and activate the automatic brakes only when a collision is unavoidable. However, the latest systems have been improved to avoid the collision itself.

Although CAMS are promising technologies for reducing pedestrian/vehicle accidents, they have been slow to spread in the market. One reason is that there are currently no standardized test methods for evaluating their safety performance. In order to expand the use of CAMS, it is essential to establish an institutional basis or functionality such as safety standards or assessments, based on appropriate evaluation methodologies.

This paper summarizes our study and proposes a protocol for evaluating the performance of CAMS. It also estimates the reduction in pedestrian fatalities or injuries by using CAMS.

EVALUATION TEST

TEST METHOD

In this study, we define the performance of CAMS as the detection of pedestrians in the path of the vehicle, and collision avoidance by the activation of automatic brakes, excluding collision avoidance by braking action of the driver in response to a warning. Thus, we evaluate the functions of the systems only.

As the test method, a test vehicle was driven toward a pedestrian dummy set up on the test course and the collision avoidance results were recorded (Figure 1).

We also confirmed that the jigs for fixing the dummy did not affect the detection functions of the camera and radar system.

Table 1 shows the test conditions. Daytime, dry road surface, side-facing pedestrian, black clothing (pedestrian), and center position were selected as the "standard test conditions" while assuming real-world traffic scenarios.

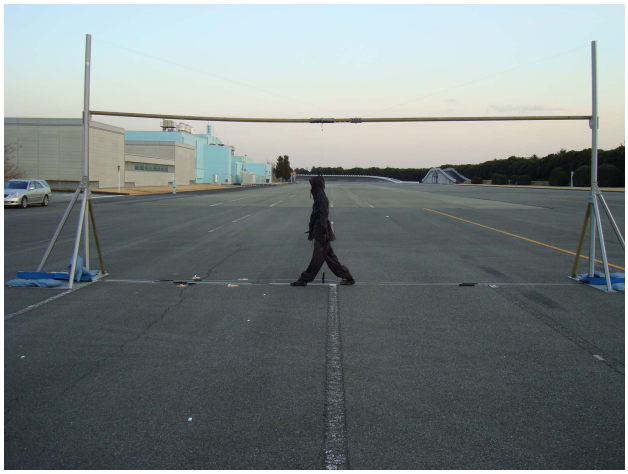

Figure1. Test setup.

Table 1 – Specifications of tested vehicles.

Item	Condition
Test vehicle	A (imported), B (domestic)
Detection sensor	(A) camera, laser and radar, (B) stereo camera
Test speed	5–60 km/h (interval of 5 km/h)
Environment	day, night
Surface	dry, wet
Dummy position	vehicle center, offsets
Dummy orientation	front, side
Dummy color	black, white, gray, flesh-color

TEST RESULTS

VEHICLE SPEED AND COLLISION SPEED

The collision avoidance results were largely dependent on the speed of the vehicle. A collision with the pedestrian dummy was more likely to be avoided at low speed, and the collision probability increased as the speed increased.

However, the results were accompanied by uncertainty and variation even under the same conditions. The

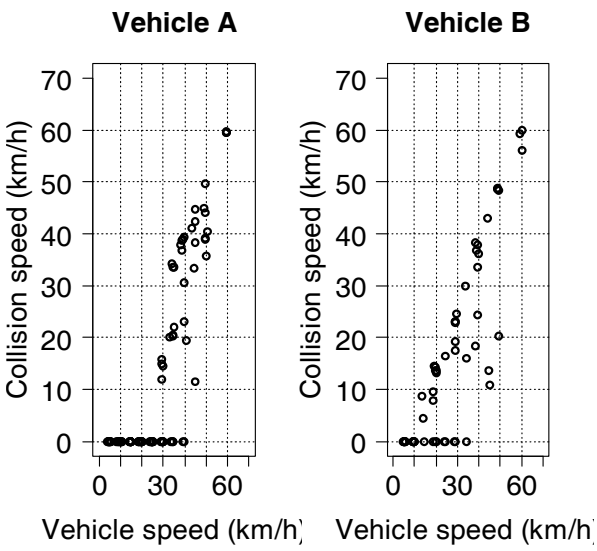

Figure2. Vehicle speed and collision speed.

results were divided into three different patterns: i) collision was avoided, ii) collision occurred with deceleration, and iii) collision occurred without deceleration (CAMS was apparently not activated).

COLLISION / COLLISION AVOIDANCE

Figure 3 shows graphs of the results based on whether or not a collision was avoided. In the graphs, each point on the 1 or 0 line indicates a collision or stop,

respectively. For both Vehicles A and B, the results of collision or stop were variable and unstable at speeds of around 20 to 40 km/h.

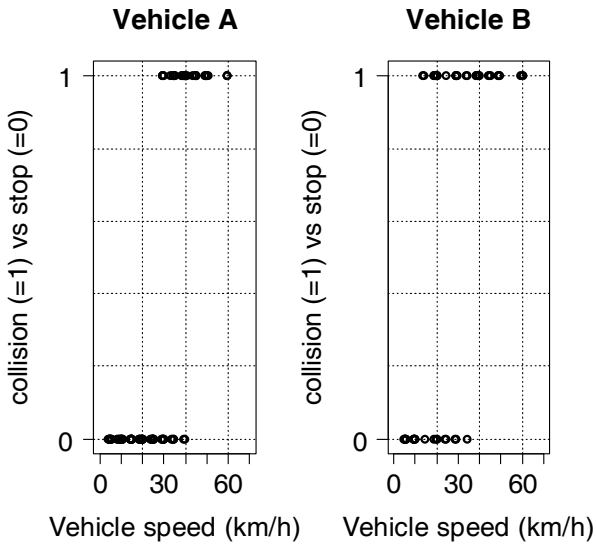

Figure3. Collision and stop distribution.

DEFINITION OF PERFORMANCE

USE OF LOGISTIC REGRESSION METHOD

Since the uncertainty in the collision avoidance results seemed to be an inherent part of the performance of CAMS, we incorporated it in the definition of performance. To do this, we regarded collision avoidance as a probabilistic event.

By applying a logistic regression model, in which "p" is the probability of collision with the pedestrian dummy, and vehicle speed "x" is an explanatory variable, when using CAMS under the standard test conditions, we defined the collision probability "p(x)" as the performance of CAMS:

$$p_\theta(c=1\,|\,x)=\frac{\exp(\beta_0+\beta_1 x)}{1+\exp(\beta_0+\beta_1 x)}$$

where, c takes one of two values, 1 for collision or 0 for collision avoidance. The parameter of this model is $\theta = (\beta_0, \beta_1)$, which can be determined from the experimental results. Collision avoidance is the exclusive event of "$p(x)$"; hence "$1 - p(x)$" indicates the collision avoidance probability.

APPLICATION EXAMPLES

In order to verify the effectiveness of the performance evaluation using this logistic regression model, we applied the model to several experimental results.

DIFFERENCES BETWEEN VEHICLE MODELS

Table 2 shows the parameters that were determined from the experimental results under the standard test conditions for both Vehicles A and B. The values in the table were confirmed to be statistically significant at the significance level of 5%. Figure 4 compares the performance for Vehicles A and B.

The overall collision avoidance performance of the CAMS is higher in Vehicle A than Vehicle B. Vehicle A stably avoids collisions up to a speed of 20 km/h, and then gradually loses the ability to avoid collisions at speeds from 20 to 40 km/h. Thus, the performance of CAMS in Vehicle A was very sensitive to speed and had so-called "sharpness". In contrast, the collision avoidance performance of the CAMS in Vehicle B showed a less sharp change up to a speed of 40 km/h.

Table 2 - Estimated model parameters

	A	B
β_0	−11.068	−3.329
β_1	0.335	0.165

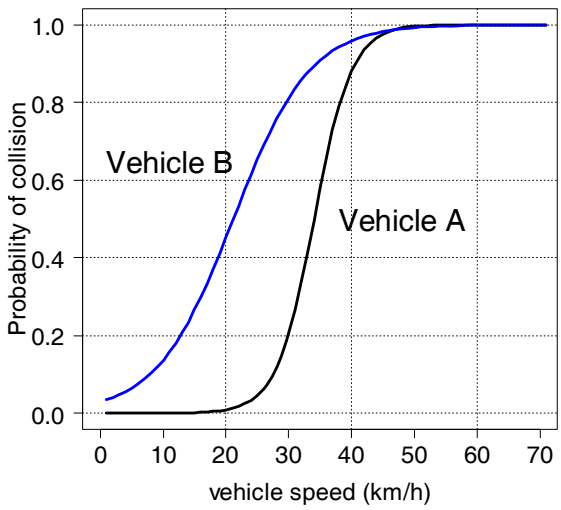

Figure4. Comparison of Vehicles A and B.

DIFFERENCES BETWEEN DUMMY ORIENTATIONS

We examined the performance difference for the identical CAMS under different experimental conditions. Table 3 and Figure 5 show the results for the identical CAMS in Vehicle B using different dummy orientations (front-facing and side-facing).

Table 3 - Estimated model parameters.

	Front	Side
β_0	−5.242	−3.329
β_1	0.144	0.165

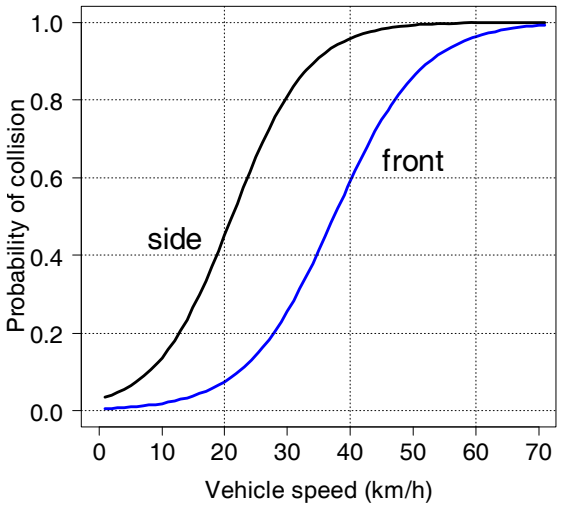

Figure5. Performance comparison of dummy orientation.

Collision with the front-facing dummy was more easily avoided than with the side-facing dummy. However, parameter β_1, which indicates the sensitivity to vehicle speed, does not differ much between the two orientations. Meanwhile, parameter β_0 (intercept) of the side-facing dummy is slightly higher than that of the front-facing dummy. Thus, the front-facing dummy is more easily detected, although the sensitivity to vehicle speed is the same in both orientations.

ANALYSIS OF PERFORMANCE OF CAMS

WARNING TIMING AND BRAKE TIMING

As the two functions of CAMS are detection of pedestrians and automatic braking, we used the warning timing (TTC [s]) as a measurement of the detection function, and the braking timing (TTC [s]) as a measurement of the automatic brake function. (TTC means Time To Collision.)

Figure 6 shows the distribution of warning timings, braking timings, and collision avoidance results under the standard conditions. As for Vehicle A, only the braking timing has a significant influence on the collision avoidance result and collision avoidance is achieved if TTC is longer than 0.6 second. In contrast, there is a positive correlation for Vehicle B between warning timing and braking timing, and collision avoidance is achieved if the warning timing is longer than 1.2 seconds and the braking timing is longer than 0.6 second although collision avoidance is not constantly achieved and the results vary.

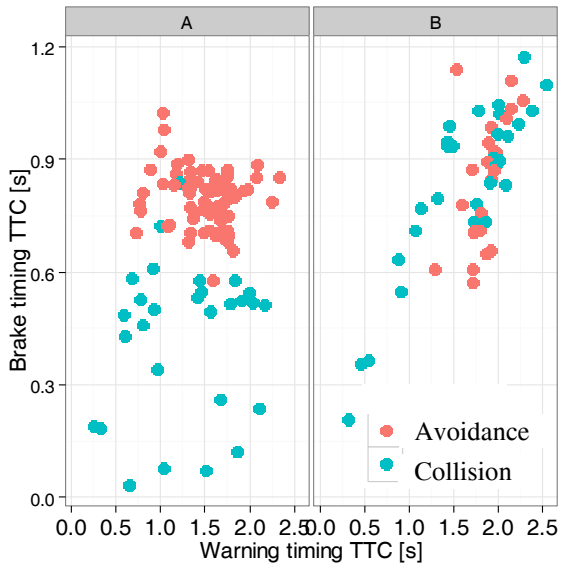

Figure6. Warning timing, brake timing and collision avoidance.

DRIVER'S RESPONSE TIME

Figure 7 shows the distribution of ΔT which is the time between a warning being issued and automatic brake activation. The values of ΔT are distributed widely in the range between 0.0 second and 2.0 seconds both for Vehicles A and B, while it is commonly considered that it takes at least 1.0 second for less attentive drivers to understand the meaning of a warning and respond to it appropriately.

For Vehicle A, ΔT was shorter than 1.0 second in 75% of all cases. As Figure 6 indicates, that there is no correlation between warning

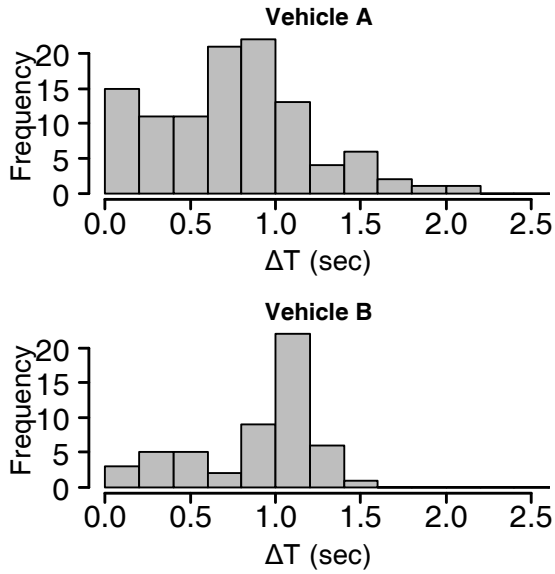

Figure7. Distribution of ΔT.

timing and braking timing; in many cases the automatic brake is activated without waiting for the driver to respond. Also, ΔT values vary widely and

there is no tendency of keeping ΔT values above a certain level in order to wait for the driver's reaction. Thus, under the design specifications of Vehicle A's CAMS, the priority is automatic brake activation.

For Vehicle B, in many cases ΔT is longer than 1.0 second. Compared with Vehicle A's CAMS, Vehicle B's CAMS tends to wait for more than a certain time needed for the driver to operate the brakes.

As a result of analyzing the difference in collision avoidance performance between the two vehicle models equipped with CAMS, the main factor is the timing of automatic brake activation. It is also found that in order to increase the collision avoidance probability, it is more effective to activate the automatic brake, rather than to wait for the driver to respond to a warning. On the other hand, designing CAMS focusing on automatic brake timing means reducing the time necessary for the driver to operate the brakes in response to a warning, which effectively means limiting the driver's control.

Naturally, there is a trade-off between maintaining the driver's control and the collision avoidance performance of CAMS. Whether priority is given to the driver or to the system depends on the difference in safety concept or design philosophy.

ESTIMATED EFFECTS

We estimated the effects on reducing pedestrian/vehicle accidents based on the defined performance of the CAMS.

ESTIMATES OF FATALITIES

The Institute for Traffic Accident Research and Data Analysis (ITARDA) releases data on pedestrian/vehicle fatalities and injuries by four-wheel vehicles. According to this data, which is organized by hazard recognition speed, the number of fatalities during the 5-year period from 2006 to 2010 was 7,997 and the distribution by hazard recognition speed is indicated by the bars in Figure 8. We define this distribution as N.

By regarding the hazard recognition speed of "N" as the vehicle speed, the distribution of fatality reduction upon activation of CAMS, which is expressed by (1 – p(x)) N(x), can be calculated by multiplying the hazard recognition speed by the collision avoidance probability.

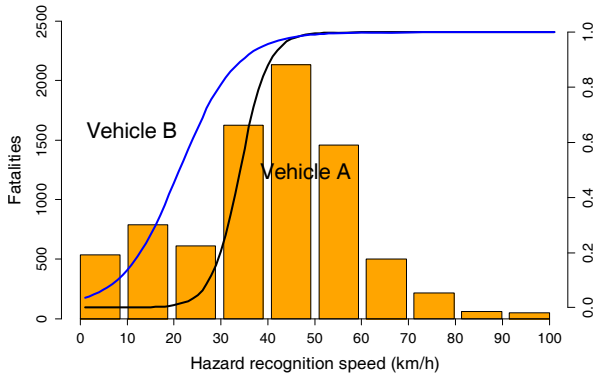

Figure8. Distribution of pedestrian fatalities and probability of collision with CAMS.

Figures 9 and 10 show the pedestrian fatality distribution assuming a 100% implementation rate for Vehicle A or Vehicle B, respectively. Pedestrian fatalities will be reduced by avoiding collisions. The pedestrian fatality reduction effects are greater at low and medium speeds at which the performance of CAMS is high.

The expected reduction in number of fatalities can be calculated by the following formula, in which ΔN denotes the reduction in number of pedestrian

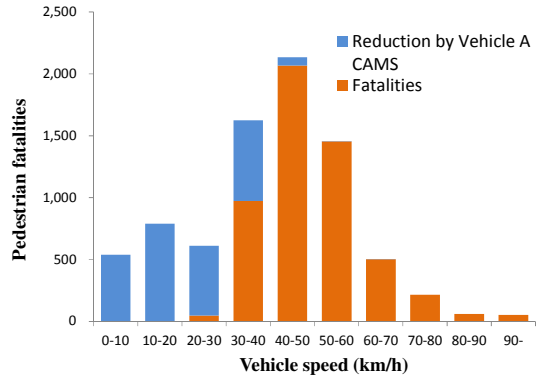

Figure9. Estimated pedestrian fatality reduction for Vehicles A.

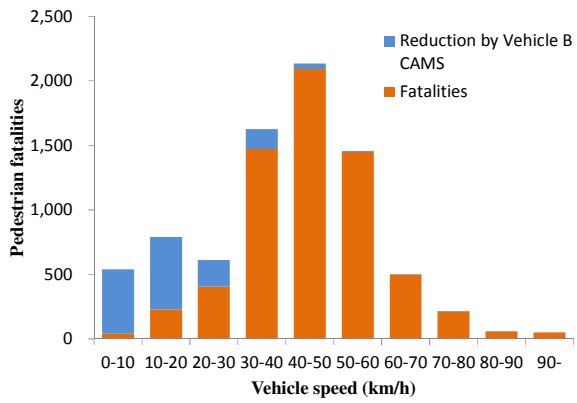

Figure10. Estimated pedestrian fatalities reduction for Vehicles B.

fatalities, and p(x) denotes the collision probability for vehicle speed "x".

$$\Delta N = \int (1 - p(x))N(x)dx$$

For Vehicle A, ΔN is calculated to be 2,611, giving an expected fatality reduction rate of 33%. For Vehicle B, ΔN is calculated to be 1,462, an expected reduction of 18%.

ESTIMATES OF SEVERE INJURIES

We calculated the expected reduction in number of severe injuries using the same method as above. Figures 11 and 12 show the distribution of pedestrian severe injuries in 2009 and the results reflecting the reduction effect for Vehicles A and B, respectively. The severe injury rate is higher at low and medium speeds where the CAMS collision avoidance probability is higher. This produces significant effects at low and medium speeds, and so the reduction rate for severe injuries is expected to be 70% for Vehicle A and 45% for Vehicle B.

The above estimates are based on the following assumptions: i) CAMS provides the same level of performance under various real-world traffic circumstances as under the basic conditions, ii) the number of fatalities or severe injuries in each accident case is counted as 1, and iii) the implementation rate for Vehicle A or B among the corresponding number of vehicles in the data is 100%.

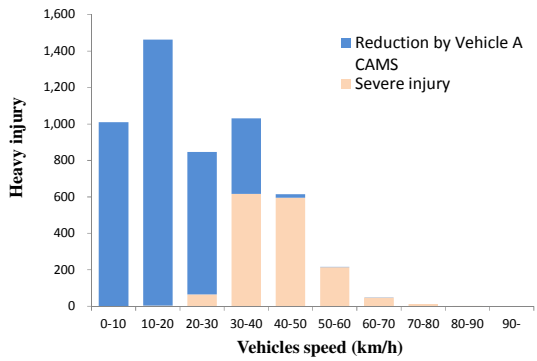

Figure11. Distribution of pedestrian severe injuries by Vehicle A.

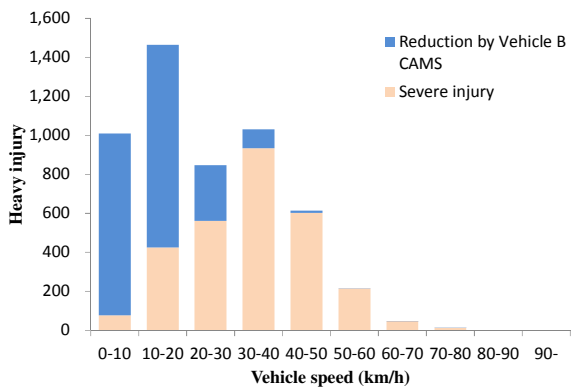

Figure12. Distribution of pedestrian severe injuries by Vehicle B.

CONSIDERATIONS AND CONCLUSIONS

In this study, by regarding collision avoidance by CAMS as a probabilistic event, we defined the expected collision probability obtained by regression calculation as the performance of CAMS. We also examined the variation in performance resulting from differences in vehicles or condition settings. We consider that this definition of the performance of CAMS brings the following benefits.

The collision avoidance performance can be evaluated while taking into account the uncertainty in the collision avoidance results. The conventional safety standards regard the safety performance as being definitive. For example, in the area of crash safety, the standard requires limiting the injury value (HIC value for the head) to a certain level for a collision speed lower than a specified value. However, for CAMS, it is more realistic to consider collision avoidance as a probabilistic event due to the variation of real-world traffic circumstances and the related technical difficulties.

The main focus of automotive safety has been shifting from crash safety (passive safety) to prevention safety (active safety). This indicates a shift from definitive values to values with uncertainty, and from certainty to uncertainty expressed by probability.

In Japan, about 100 pedestrians are involved in vehicle accidents resulting in fatality or injury every day. We consider that the accident reduction effect of CAMS will become obvious as it spreads in the market, and the effect will converge with the performance (the expected value) shown by the regression line of this system (the law of large numbers).

The collision avoidance performance can be defined for all speed ranges by using the logistic regression model. As a result, the effects on reducing pedestrian accidents, which are distributed over a wide speed range, can be evaluated for a broad range of speeds rather than just a specific speed.

As a performance requirement of the safety standard, we propose limiting the collision probability to less than a certain value for a certain speed, or setting the expected value of fatality reduction by utilizing the wide performance range.

Also, the performance of CAMS can be rated by expressing the safety performance as an expected value for damage mitigation, which is also useful for new car assessment programs.

FUTURE ISSUES

In defining the safety performance by probability, the following issues should be considered.

In principle, we regard collision avoidance as a probabilistic event for every case of CAMS activation, and so collisions due to a malfunction of CAMS are not distinguished from collisions as probabilistic events. As a result, defect investigations may not be fully implemented, leaving defective units uncollected. Therefore, it is necessary to establish an appropriate standard that parallels the stringent defect investigations and recall procedures.

In this study, we proposed an evaluation method based on binomial values, namely whether or not collisions with pedestrians are avoided. The results show that if a collision occurs at a sufficiently low speed, the damage can be significantly reduced. It might be practical to set certain threshold values since minor collisions cause only small damage. Therefore, evaluation methods that consider the effectiveness of deceleration should also be considered.

In the accident analysis results, pedestrian injuries are caused not only by colliding with vehicles, but also by hitting the road surface, curb, etc. upon falling after the collision. If we take this into consideration, the presence or absence of collision is still the highest indicator regardless of the collision level.

The pedestrian dummy used in this study was the size and shape of an average Japanese man. This visible condition setting is valid for evaluating systems that incorporate a detection camera; however, its equivalence to the human body has not been fully confirmed for systems that incorporate detection laser/radar. To ensure accurate evaluation of the systems, it is necessary to use a pedestrian dummy that has radio wave properties (reflecting properties) equivalent to the human body. It is also important to use a dummy that incorporates motion since many real-world traffic accidents involve moving pedestrians. We will continue studying these issues in our work at NTSEL.

ACKNOWLEDGMENTS

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REFERENCES

1. ITARDA Information, No. 90, pp. 3–4 (September 2011), Institute for Traffic Accident Research and Data Analysis.
2. Traffic Accidents Investigation and Analysis Report, Chapter 3-3 (May 2012), Institute for Traffic Accident Research and Data Analysis.
3. Ando, K., et al. “An Evaluation Protocol for Collision Avoidance and Mitigation Systems and its Application to Safety Estimation (First Report),” JSAE Spring 2012, Paper Number 12-20125328.
4. Ando, K., et al. “An Evaluation Protocol for Collision Avoidance and Mitigation Systems and its Application to Safety Estimation (Second Report),” JSAE Autumn 2012, Paper Number 209-20125738.