DEVELOPMENT OF PRE-CRASH SAFETY SYSTEM WITH PEDESTRIAN COLLISION AVOIDANCE ASSIST

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ABSTRACT

A new pre-crash safety (PCS) system with pedestrian collision avoidance assist has been developed. This system is capable of detecting both vehicles and pedestrians, and helps the driver to avoid a collision by automatically braking the vehicle by up to 40 km/h, one of the highest rates of deceleration for a PCS system in the world. Pedestrian detection is enabled by a sensing system that combines millimeter wave radar and a stereo camera. This system is capable of stable object detection regardless of day or night. At night, the system uses near infrared projectors to enhance the detection performance of the camera.

This paper describes the core technology for achieving this system, including brake control technology for decelerating the vehicle by up to 40 km/h to help avoid a collision, and recognition technology capable of detecting pedestrians walking quickly across a road.

The collision avoidance brake control technology achieves higher and more accurate deceleration than conventional systems, and is robust against variations in brake effectiveness. These variations are suppressed by the control algorithm, which uses the distance to the object and the deceleration as feedback parameters. As a result, the target deceleration performance may be achieved even under certain conditions of brake effectiveness variation. In addition, the timing of braking start was designed not to interfere with collision avoidance operations performed by the driver. The deceleration and jerk (i.e., the deceleration gradient) were also determined considering the risk of the driver becoming dependent on or over-confident in the system.

An effective recognition technology that helps to prevent a wider range of accidents should be capable of detecting pedestrians quickly crossing a road. To further this goal, the response of the position detection filter of the millimeter wave radar was enhanced, and new algorithms were developed for collision judgment as well as the fusion between the millimeter wave radar and stereo camera. These measures enable highly accurate collision judgment for pedestrians crossing a road.

1. INTRODUCTION

PCS systems judge the probability of a collision based on the position and relative speed of the driver's vehicle with respect to an object, and either help the driver to avoid the collision or help to mitigate collision damage by activating devices such as warnings, brake assist, automatic braking, and the like. Since Toyota developed the first commercial PCS system in February 2003, the technology has advanced to include detected pedestrian as well as frontal collisions at intersections [1-2]. In contrast, most conventional automatic braking systems were designed to activate only when a collision is unavoidable, help mitigate the damage caused by the collision. However, new systems have since been developed that are capable of avoiding some types of collisions automatically [3].

This paper describes a newly developed PCS system with pedestrian collision avoidance assist. This system is capable of detecting both vehicles and pedestrians, and helps the driver to avoid a collision by automatically braking the vehicle by up to 40 km/h. This is one of the highest rates of deceleration for a PCS system in the world, however, the system cannot fully replace driver attention to surround.

The following sections detail the aims of the system, the development issues, and the core brake control and recognition technologies that were developed to resolve these issues. This system was installed on the Lexus LS launched in September 2012.

2. SYSTEM OUTLINE

This section describes how the aims of the PCS system with pedestrian collision avoidance assist were determined based on the analysis of real-world accidents, the development items to achieve these aims, and the system configuration.

2.1 System Aims and Development Items

According to traffic accident statistics in Japan, rear-end collisions are the most frequent type of accident, and accidents between vehicles and pedestrians account for the highest proportion of fatal accidents [4]. Furthermore, the relative speed distribution data of these accidents shows that more than 80% of rear-end collisions and more than 90% of vehicle-pedestrian accidents occur at a relative speed of 40 km/h or less (Figure 1).

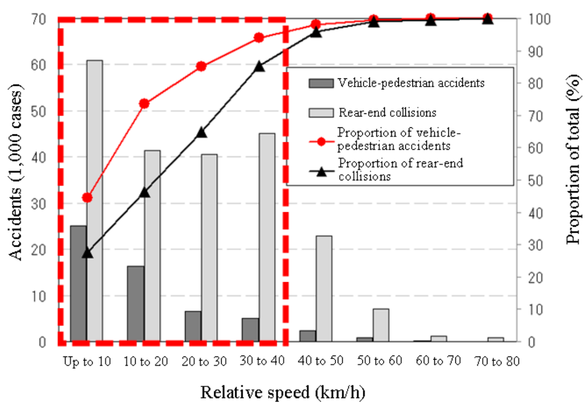

Figure1. Relative speed distribution of rear-end collisions and vehicle-pedestrian accidents (source: Institute of Traffic Accident Research and Data Analysis (ITARDA) 2010 Report).

The same traffic accident statistics show that most (76%) accidents between vehicles and pedestrians occur when the pedestrian is crossing a road (Figure 2).

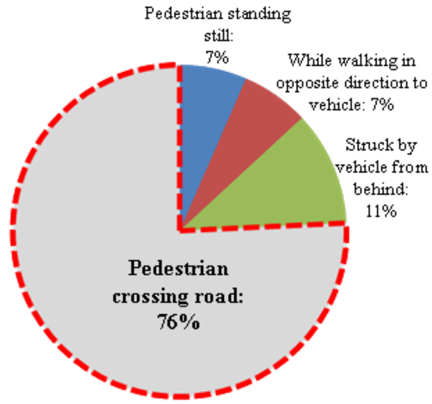

Figure2. Distribution of vehicle-pedestrian accident types (source: ITARDA 2010 Report).

In addition, time distribution statistics of fatal accidents between vehicles and pedestrians indicate that most such cases occur at night (Figure 3).

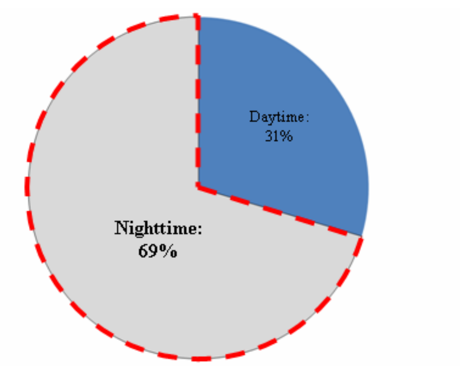

Figure3. Daytime/nighttime distribution of fatal vehicle-pedestrian accidents (source: "Details of Fatal Traffic Accidents and Results of Road Traffic Law Enforcement in 2011" (in Japanese), Traffic Bureau of the National Police Agency of Japan).

Based on these statistics, this development aimed to achieve a system capable of detecting both vehicles and pedestrians walking quickly across a road regardless of day or night. The speed reduction target was set to 40 km/h.
The following two development items were identified to achieve these aims.
- Automatic brake control technology with high deceleration
- Early collision probability judgment and recognition technology for pedestrians crossing a road

The following sections describe the development of these technologies in more detail.

2.2 System Configuration

Figure 4 shows the configuration of the system. It consists of a pre-crash sensor system, which judges the probability of a collision, and collision avoidance assist devices. The pre-crash sensor system includes various peripheral monitoring sensors such as a millimeter wave radar, stereo camera, and the like, and a PCS ECU. This system is capable of stable recognition of objects regardless of day or night. At night, the system uses near infrared projectors to enhance the detection performance of the camera.

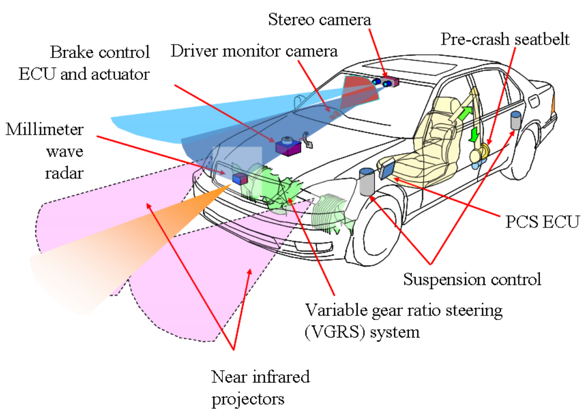

Figure4. Configuration of PCS system with pedestrian collision avoidance assist.

The pre-crash sensor system detects vehicles, pedestrians, and other objects, judges the collision probability using parameters such as the position, speed, and predictive courses of the driver's vehicle and object, and then activates the collision avoidance assist devices based on this probability. Figure 5 shows the operation sequence of each device. If the system detects a danger of a collision, it urges the driver to take evasive action through a warning buzzer and meter display. In this case, if the driver monitor camera detects that the driver is not paying sufficient attention to the road ahead due to distraction or drowsiness, an earlier warning is given and warning braking is performed to attract the driver's attention. If there is a higher danger of a collision, the system acts to assist evasive action by the driver. For example, the variable gear ratio steering (VGRS) system sets the appropriate steering gear ratio to help the driver steer around the object, the suspension control activates to help prevent the nose of the car diving forward, and the pre-crash brake assist increases the emergency braking force when the driver presses the brake pedal. Then, if a collision is unavoidable, the pre-crash seatbelt is operated so as to retract the seat belt automatically, and the pre-crash brake is operated to assist the driver avoid the collision.

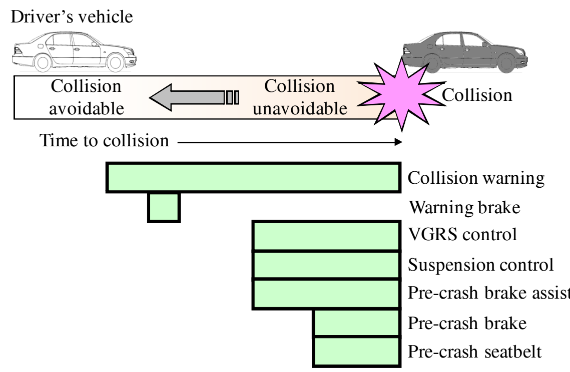

Figure5. Operation sequence of collision avoidance assist devices.

3. HIGH-DECELERATION AUTOMATIC BRAKE CONTROL TECHNOLOGY

This system aims to help mitigate collision damage by reducing the vehicle speed by up to 40 km/h, the brakes must be capable of achieving high deceleration. In addition, to help avoid an object, the brake control must generate the required deceleration accurately so that the vehicle does not stop in front of the object unless necessary (Fig. 6). To achieve these aims, a new deceleration feedback control algorithm was developed. The braking start timing, deceleration, and jerk were determined considering the risk of the driver becoming dependent or over-confident in the system. These points are described in the following sections.

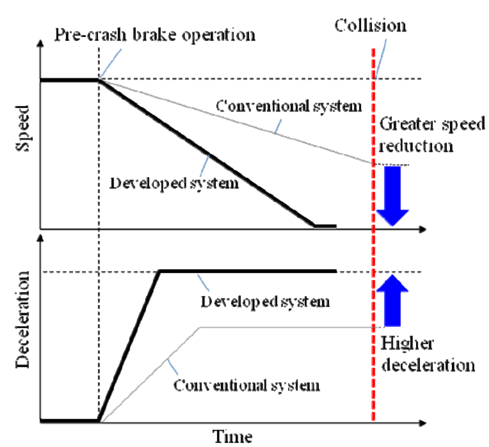

Figure6. Expansion of automatic braking effect.

3.1 Deceleration Feedback Control Algorithm

Figure 7 shows the flow from judgment that a collision is probable to activation of the automatic braking system.

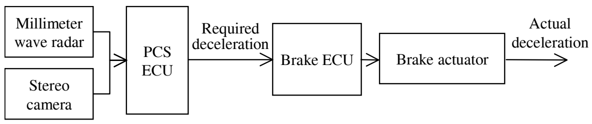

Figure7. Flow of deceleration controlled by automatic braking system.

First, the sensor detects an object and the PCS ECU judges the collision probability. If the probability is higher, the PCS ECU sends the required deceleration signal to the brake ECU. The vehicle is then decelerated via the brake actuator. However, the actual deceleration varies in accordance with a large number of factors, such as the state of the brake pads, vehicle weight, road surface friction (μ), and the like. Figure 8 shows the difference between the actual deceleration and the deceleration required to avoid an object at a relative speed of 40 km/h. The figure shows actual deceleration results from tests performed under two different conditions for the brake pad state, vehicle weight, and the like.

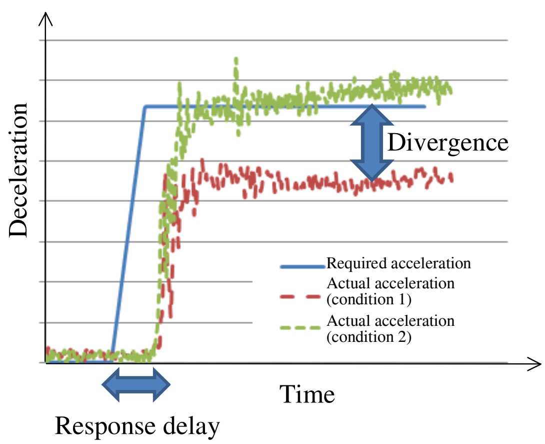

Figure8. Difference between required and actual deceleration (stationary object, relative speed: 40 km/h).

Figure 8 indicates that a response delay occurred before the actual deceleration is generated. In addition, the final deceleration diverged from the required deceleration depending on the test conditions. Consequently, a new deceleration feedback control algorithm was developed to stably reduce the relative speed of the vehicle by up to 40 km/h under various conditions that cause actual deceleration to fluctuate. Figure 9 shows a block diagram of this feedback control.

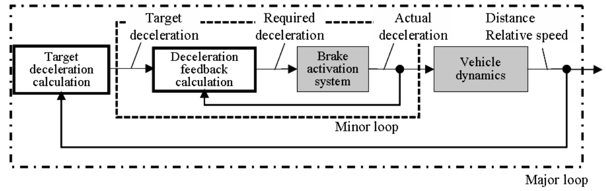

Figure9. Deceleration feedback control.

First, the target deceleration calculation module in the major loop feeds back the distance, relative speed, and the like detected by the sensors and calculates the target deceleration required to avoid the object. Next, the deceleration feedback calculation module in the minor loop feeds back the actual deceleration and calculates the required deceleration by correcting the target deceleration. These steps enable a brake control that is robust against variations in brake effectiveness by suppressing their impact.

3.2 Deceleration Control Considering System Dependence and Over-Confidence

The automatic brake may intervene depending on the collision probability judgment. However, if the timing of the intervention is too early, the driver may start to feel that objects can be avoided without manual brake operation; this is known as system dependence. Since the driver must always remain in control of the vehicle and be aware of the surrounding, PCS systems are designed simply to assist manual operation by the driver by helping to compensate for errors in cognition and decision making. Therefore, the brake control is designed to reduce the risk of the driver becoming dependent on or over-confident in the system. To achieve this, the braking start timing, deceleration, and jerk were designed not to interfere with collision avoidance operations performed by the driver, thereby reducing the livelihood of dependence and over-confidence.

3.2.1 Braking start timing There are two types of collision avoidance operations: avoidance by braking and avoidance by steering. Figure 10 shows the avoidance timing region of an ordinary driver in normal driving [5].

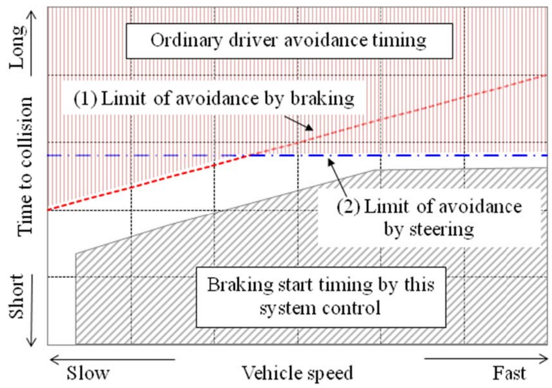

Figure10. Braking start timing of developed system.

In Figure 10, the time to collision (TTC) is calculated by the relative distance and speed. An ordinary driver is capable of avoiding a collision in the region where the TTC is longer than indicated by lines (1) and (2). The braking start timing was set to the region in which the TTC is shorter than that avoidable by manual operation. This works to prevent interference with collision avoidance operations performed by the driver, reducing dependence or over-confidence in the system.

3.2.2 Deceleration and jerk A monitoring evaluation test was carried out under the conditions listed in Table 1 to confirm the deceleration and jerk during normal braking by an ordinary driver.

Table1.
Evaluation Conditions

Vehicle speed conditions	25 km/h, 45 km/h
Braking conditions	Avoidance of object by normal braking
Test samples	208

Figure 11 shows the distribution of deceleration and jerk in normal braking obtained by the monitoring evaluation and in automatic braking by this system.

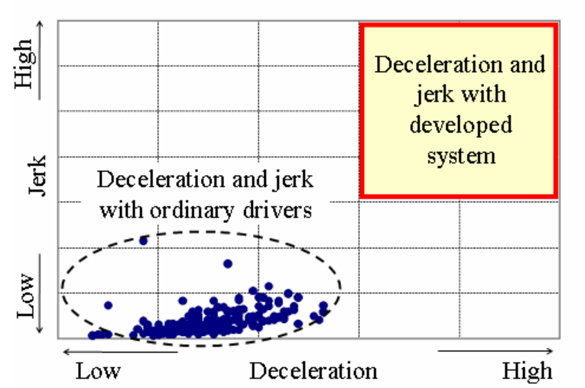

Figure11. Deceleration and jerk during normal braking by ordinary drivers.

The deceleration and jerk of the automatic braking in this system were set substantially higher than the normal braking region. This clearly differentiates normal and emergency braking and helps prevent system dependence.

4. EARLY COLLISION JUDGMENT AND RECOGNITION TECHNOLOGY FOR CROSSING PEDESTRIANS

As Figure 12 shows, braking to achieve a deceleration of up to 40 km/h when a pedestrian crosses a road requires an expanded PCS system operation region and earlier collision probability judgment. Therefore this system was designed to judge the probability of a collision with a pedestrian crossing a road and to operate the brakes at an earlier timing. This was accomplished by enhancing the horizontal position response of the millimeter wave radar, and developing new algorithms for collision judgment as well as the fusion between the millimeter wave radar and stereo camera for detecting pedestrians crossing a road. The details of these three items are described in the following sections.

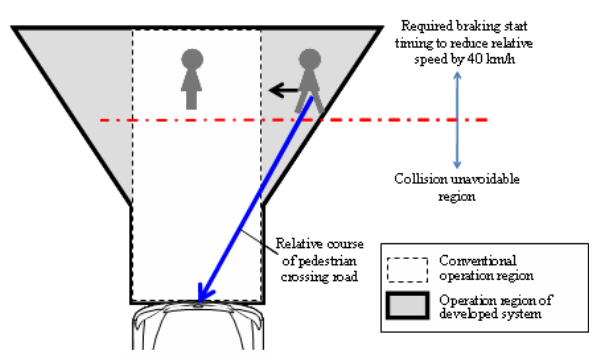

Figure12. Outline of operation for pedestrian crossing road.

4.1 Design of Millimeter Wave Radar Horizontal Position Filter

The horizontal position of an object detected by radar (i.e., the relative distance horizontally to the direction of travel) contains a certain response delay due to the filter processing within the radar ECU (Figure 13). Therefore, if a pedestrian is crossing a road quickly, the timing of entry into the collision probability judgment region is also delayed, making early collision probability judgment more difficult.

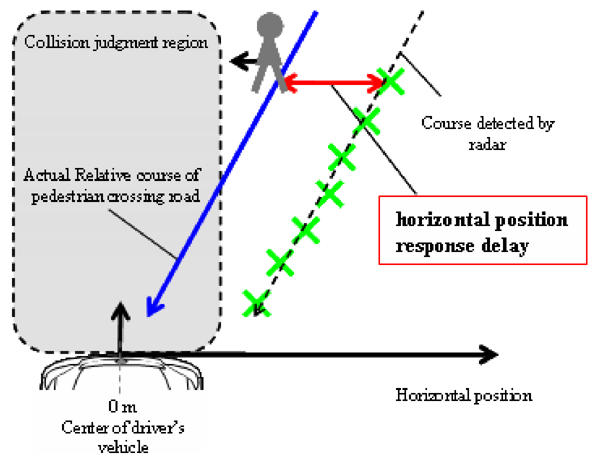

Figure13. Issue of millimeter radar wave horizontal position response.

Therefore, a filter with a faster response was designed to detect pedestrians walking quickly across a road. The conventional filter process assumes the detection of both vehicles and pedestrians. In contrast, a new filter was designed that concentrates on the detection of pedestrians crossing a road by focusing on the differences in the amount of horizontal positional changes, travel speeds, and the like between vehicles and pedestrians. This approach helps to suppress variations and to enhances response. As shown in Figure 14, the developed system has an improved horizontal position response for pedestrians crossing a road and obtains results close to the actual course of a pedestrian.

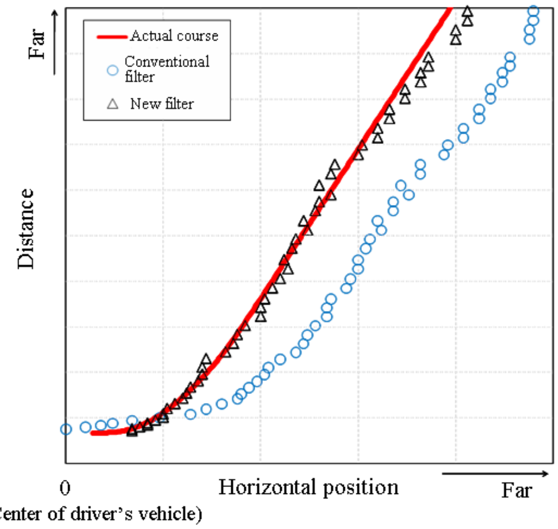

Figure14. Results of millimeter wave radar horizontal position response comparison (speed of driver's vehicle: 30 km/h, crossing speed of pedestrian: 5 km/h).

4.2 Fusion Algorithm

Since the level of radar reflection from a pedestrian is lower than a vehicle, pedestrians are detected by lowering the detection threshold value. Consequently, if only radar is used for collision judgment, it is possible that unwanted items such as metallic objects on the road may also be detected. Therefore, greater detection reliability is achieved by combining radar information with information from a stereo camera with excellent three-dimensional object recognition capabilities. Figure 15 outlines the fusion algorithm.

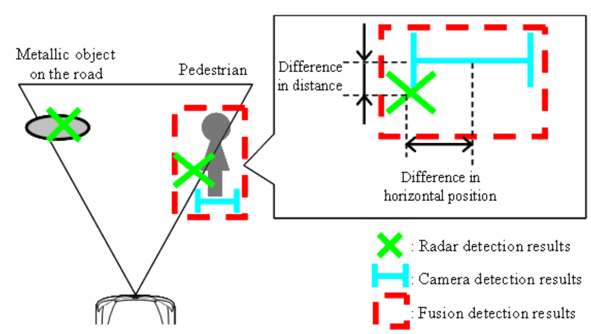

Figure15. Outline of fusion algorithm.

Fusion information is created by combining radar and camera information within certain ranges based on the differences in distance and horizontal position. The fusion algorithm allows information that cannot be detected by radar alone, such as width, height, and the like, to be used in combination with radar information.

During the fusion process, the reliability weighting attributed to the respective information from the radar and camera is adjusted in accordance with factors such as distance. This allows short-range detection, which is difficult for radar to perform, to be interpolated by the camera, thereby enhancing the accuracy of pedestrian collision judgment.
The collision judgment algorithm described in Section 4.3 uses this fusion information.

4.3 Collision Judgment Algorithm

As shown in Figure 16, a conventional system can only judge collision probability within a range inside the driver's vehicle width. Therefore, to judge the probability of collision at an earlier timing, it is necessary to expand the collision probability judgment range outside the width of the driver's vehicle. A new algorithm was developed to reduce the vehicle speed by up to 40 km/h when an object is detected outside the driver's vehicle width by determining the point of intersection between the front of the driver's vehicle and the relative course of the pedestrian crossing the road. Figure 17 outlines this newly developed algorithm.

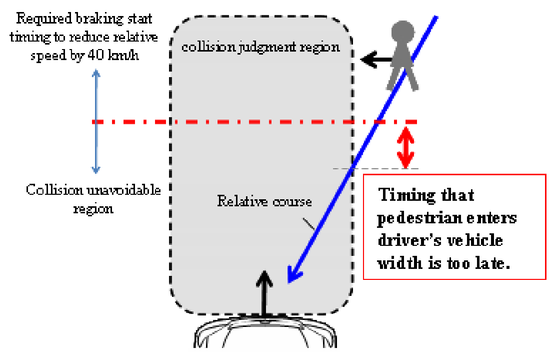

Figure16. Issue of detecting pedestrian crossing road.

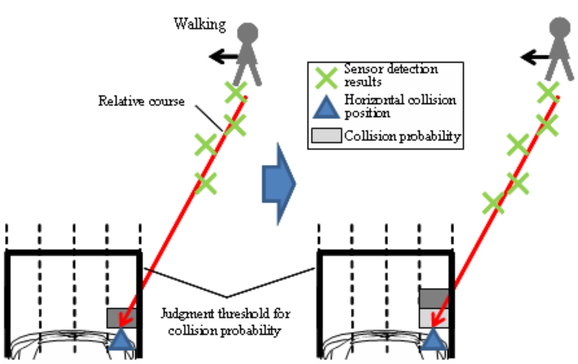

Figure17. Outline of collision probability judgment algorithm.

First, the algorithm calculates the point of intersection between the front of the driver's vehicle and the relative courses of the vehicle and the pedestrian crossing the road (i.e., the horizontal position of collision). In this process, the relative course is calculated using position information over an elapsed period of time obtained from the sensors. However, the accuracy of the sensors may cause vector variations, resulting in an unstable horizontal collision position. Therefore, the front of the vehicle is divided into regular segments and the distribution of the horizontal collision position over a set period of time is calculated as the collision probability. If the probability of collision with the front of the vehicle exceeds a threshold value, the algorithm judges that a collision is probable. The left and right diagrams in Figure 17 show time-series detection histories. The probability of a collision within the same segment increases because the same horizontal collision position segment was calculated in two successive cycles. In this way, vector variations due to sensor accuracy are reduced by judging the horizontal collision position based on the distribution over set segment and time ranges, thereby improving judgment accuracy. Finally, the collision probability outside the vehicle width is judged by combining these results with the TTC and other collision probability judgment conditions calculated using the fusion results described in Section 4.2. As a result, the vehicle speed can be reduced by up to 40 km/h even with a pedestrian crossing a road.
In addition, Figure 18 shows a scenario in which a pedestrian suddenly stops outside potential collision zone while crossing a road as an example of a false positive that conflicts with the enlarged operation range of the system.

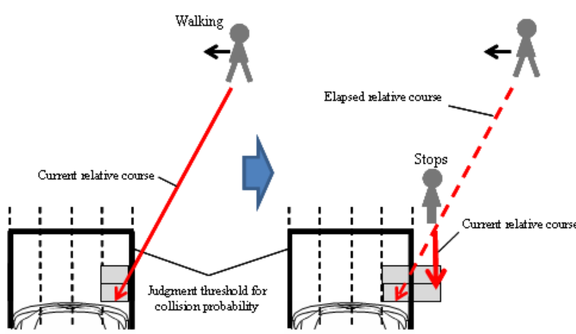

Figure18. Collision probability distribution in false positive scenario.

In this type of scenario, the pedestrian should not be detected as a possible collision object. Therefore, factors such as the segment width, collision probability adjustment calculation, and the like were optimized so that the collision probability is scattered over multiple segments rather than concentrating in one segment. This helps prevent the collision probability judgment threshold from being exceeded.

5. CONCLUSION

PCS systems have previously been developed to help mitigate collision damage by reducing the speed of common accident patterns such as rear-end collisions and frontal collisions at intersections. This paper has described the development of a PCS system with pedestrian collision avoidance assist to help reduce traffic accident fatalities and injuries. This system aims to help further reduce the number of people killed or injured in traffic accidents by enabling automatic braking with one the highest rates of deceleration for a PCS system in the world. Future goals include further enhancing the level of collision avoidance performance, developing technology to achieve omni-directional detection, and reducing costs to enable these systems to be adopted more widely. By these measures, technological development can help contribute to a safer and more comfortable mobile society.

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