

Safety Evaluation of Advanced Driver Assistance Systems as Human-machine Systems

- Systems Equipped with ACC and LKA -

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ABSTRACT: We propose an evaluation methodology to analyze the safety level of advanced driver assistance systems (ADAS) as a human-machine systems in terms of comparing the increase in the safety level during normal system operation and the decrease in the safety level during a system malfunction. We propose a concept of combined error for the human-machine system and quantify this combined error by driving simulator investigations and simulation studies. First, we investigated the drivers' behavior when avoiding rear-end collisions with a preceding vehicle when equipped with ADAS-like adaptive cruise control systems (ACC) and lane keeping assistance systems (LKA). Then, we confirmed that the risk of collision induced by overdependence on the systems was not increased when the ACC and LKA were mounted on the vehicle using simulation studies based on the concept of combined error for the human-machine system. We also confirmed that the decrease in collisions when the ADASs operated appropriately was much larger than the increase in collisions during a system malfunction.

KEY WORDS: Safety, Driving Support, Overconfidence, Accident avoidance, Human-machine system, ACC, LKA [C1]

1. Introduction

It has been debated if the risk of rear-end collisions of a vehicle will increase when a vehicle is driven with the help of multiple driver assistance systems. For example, the risk may increase due to the low attentiveness of a driver who may excessively depend on the assistance systems. As long as the advanced driver assistance system is normally operating, it is likely that the risk of collision will decrease. However, there is a fear that when it is difficult for the system to operate, the risk of a collision could increase more than the risk involved when the system is not used. Herein, we describe an evaluation methodology to quantitatively estimate the effectiveness of introducing the system. As reported by Suzuki et al. ⁽¹⁾⁽²⁾ in their previous study that evaluated the safety when the system and driver are integrated, the concept of the combined error model is adopted in our study. A trade-off analysis between the positive effects, i.e., the decrease in the risk of collision with the system when it is operating normally, and the negative effects, i.e., the increase in the risk induced by an overdependence on the system when it is difficult to operate, is performed, and an example of the analysis is described in this study. Specifically, we analyzed changes in the risk of a collision of a vehicle equipped with the adaptive cruise control (ACC) and lane keeping assistance (LKA) systems. Two approaches were adopted and combined in the analysis: one was an experiment with a driving simulator and the other was a time-series simulation of the

reliability of ADAS and the driver, wherein they were modeled as a human-machine system.

2. Collision Mitigation Effectiveness Quantification Methodology

2.1. Analysis of effectiveness of ADAS and driver as a human-machine system

To quantify the collision mitigation effectiveness when a vehicle is equipped with the system, a situation wherein it is difficult for the system to be operational should be considered in the analysis in addition that wherein ADAS is operating normally. The former situation could occur for any reason despite the probability of such an occurrence being small. Suzuki et al. ⁽¹⁾⁽²⁾ proposed a concept to estimate a driver's error when a vehicle is equipped with the system. In this concept, the reliability of the system and driver are combined, assuming that the occurrence of a situation wherein it is difficult for the system to be normally operated (hereinafter referred to as the "system error") and that wherein the driver cannot control the vehicle normally (hereinafter referred to as the "driver error") are independent. The y-axis of Figure 1(b) indicates system reliability, i.e., the system's possibility of providing a driver with support, and the x-axis indicates the driver's reliability, i.e., the driver's possibility of driving the vehicle normally. The zones surrounded by these axes express the

overall reliability. In other words, zone A in Figure 1 expresses the possible decrease in the risk of collision when the system is normally operational, and zone B expresses the possible increase in risk when it is difficult for the system to operate. In zone B, there is a fear that the risk of collision could increase due to the driver's dependence on the system. When the area of zone A is larger than that of zone B, the collision probability of the vehicle equipped with the system is lower than that of a vehicle not equipped with the system, implying that there are benefits when the system is applied in practice. Note that the reversed L-shaped zone in Figure 1 (the "total error") indicates the error probability of a vehicle controlled by a driver and system (or the combined collision probability of a vehicle equipped with the system).

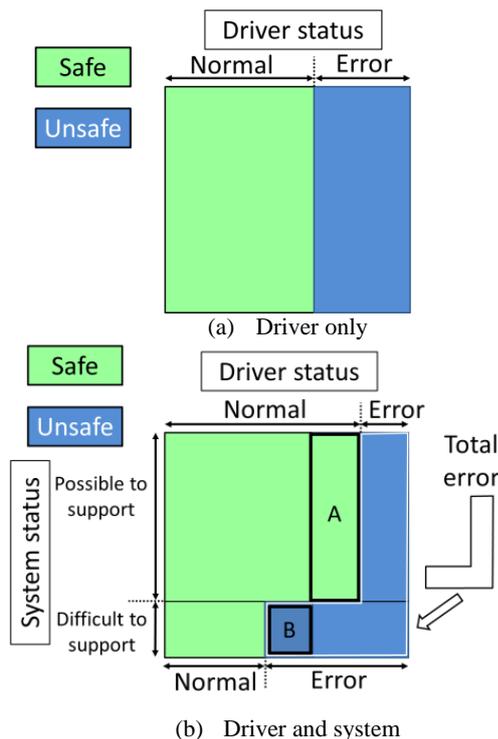


Fig. 1 Combined error model to estimate driver and system reliabilities.

2.2. Analysis of system effectiveness by Monte Carlo simulation

This section describes how to quantitatively compare the positive to negative effects, which are represented in zones A and B, respectively, which will be obtained by introducing the system. In this analysis, the driving simulator test (driving test with a simulator) and simulations have been combined to determine whether the increase in collision probability is distinguishable when a vehicle is equipped with ACC and LKA. The area ratio between zones A and B is also discussed. Monte Carlo simulation was applied to estimate driver and system reliabilities. The state variables used in the model are summarized in Table 1. The error interval of system and continuation time (system error duration), which are state variables related to system reliability, were determined as shown in Table 1 through suggestions from researchers who were engaged in the technical development of these systems for car manufacturers. State variables related to driver reliability were determined on the basis of driving simulator

investigations. The drivers' error interval was determined to be 13 s from research concerning intervals of inattentive driving when drivers were manipulating a car navigation system. This research was reported by Morita et al. (3).

Table 1 State variables in simulation model and detail of input data for each variable.

State variables	Detail of input data
R/T for risk event #1	Figure 6(a)
Drivers' reaction time to risks	
R/T for risk event #2	R/T for risk event #2 tended to become longer than R/T for risk event #1 (Figure 6(a)) by 0.4 seconds. (Suzuki et al. (4))
Drivers' reaction time to risks in the case of a system error	
Time allowance for Risk Avoidance (Tra)	Calculated with Equation (1) using Figure 6(b); deceleration
Error interval of driver	13s
Error interval of system	300 ± 30 s (Standard deviation)
Error duration of system	30 ± 5 s (Standard deviation)

When a vehicle not equipped with the system is driven by a driver, the simulation is conducted on the driver's reliability axis, as shown in Figure 2. Two states, one wherein a driver is driving normally, i.e., attentive driving without being distracted, and the other wherein he/she is driving inattentively, were simulated as a time-series reaction time simulation of the driver's reaction time. To simplify the model, the cause of collision, such as sudden deceleration of the leading vehicle, was assumed to occur when the driver was distracted, i.e., at the start of the driver's error. The variables were derived from the driver behavior database, which was obtained by experiments with a driving simulator. If the duration of the error state was longer than the time allowance for risk avoidance (Tra), then the collision was bound to occur. For example, it is possible to estimate the time allowance for risk avoidance with the stopping distance algorithm (ISO/DIS15623(5)) while quantifying the risk of a collision into the leading vehicle. The time allowance was derived from the algorithm and is expressed by Equation (1). The probability of an accident (probability of collision) is the ratio of the number of actual occurrences of a collision to that of collision risks (the number of driver errors).

$$T_{ra} = \frac{1}{2} V_2 \left(\frac{1}{a_1} - \frac{1}{a_2} \right) + \frac{y}{V_2} \quad (1)$$

T_{ra} : Time allowance for Risk Avoidance [s]

V_2 : Speed of following vehicle (subject vehicle) [m/s]

a_1 : Average deceleration of leading vehicle [m/s²]

a_2 : Average deceleration of following vehicle (subject vehicle) [m/s²]

y : Inter-vehicular distance [m]

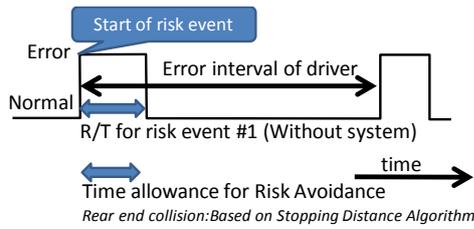


Fig. 2 Simulation model of a vehicle not equipped with the system.

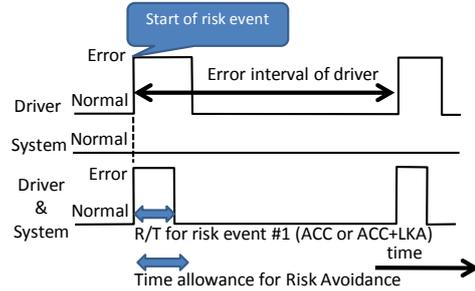
The remainder of this section outlines the simulation when a vehicle is equipped with the system. Three cases are considered, and they are classified on the basis of the timing of recovery from the system error state, i.e., when it is difficult for the system to operate, to the normal state. In the time-series simulation using Monte Carlo simulation, the time when both driver and system fell into the error state was determined by the recovery timing from the error based on the models illustrated in Figures 3(a)-(c). This time was compared to the time allowance for risk avoidance to determine whether the collision occurred. Figure 3 shows a schematic of the error duration for a vehicle controlled by a driver and system; there are three cases that can be classified on the basis of the timing of the recovery from the system error state to normal state.

“Driver & System” in Figure 3(a) indicates the combined error duration of a vehicle controlled by a driver and system when driver and system errors do not simultaneously occur. In Figure 3(b), it indicates the combined error duration of a vehicle controlled by a driver and system when the driver and system errors simultaneously occur. In Figure 3(c), it indicates the combined error duration of a vehicle controlled by a driver and system when the periods of driver and system errors partially overlap. The state variables in Table 1 were used in these models, and the state variables were derived from the driver behavior database, which was obtained by experiments with a driving simulator.

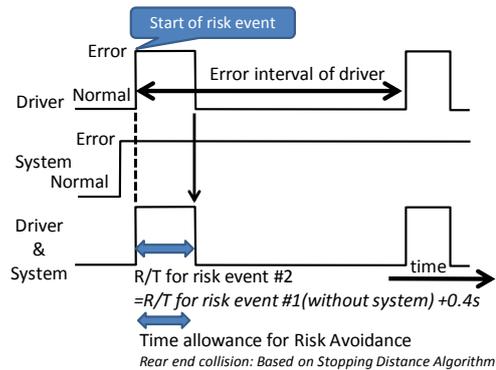
Figure 3(b) shows an example of the error duration of a vehicle deemed as a human-machine system when driver and system errors simultaneously occur. Since the system error continues longer than the driver error, the duration of the combined error, i.e., “Driver & System,” is same with the duration of the driver error.

Figure 3(c) shows the error duration when the system recovers from its error state to the normal state in a driver error. In this study, we investigated the driver behavior when using ACC equipped with alarm systems like Forward Collision Warning (FCW). Therefore, it is necessary to consider the reaction time of drivers to FCW and the system’s brake actuator operation-delay simultaneously. We have clarified that the actuator operation delay (0.3 seconds) is shorter than the reaction time of drivers after presenting FCW in a pre-test of the driving simulator investigations. So, we used the actuator operation delay as the recovery time of “Driver & System”. Note that if the driver’s braking reaction time (R/T for risk event #2) from the occurrence of the risk is shorter than this system reaction time from the occurrence of the risk, we used this driver’s reaction time as the recovery time of “Driver & System”. If this recovery time was longer than the time allowance for risk avoidance, then the collision was bound to occur. In this

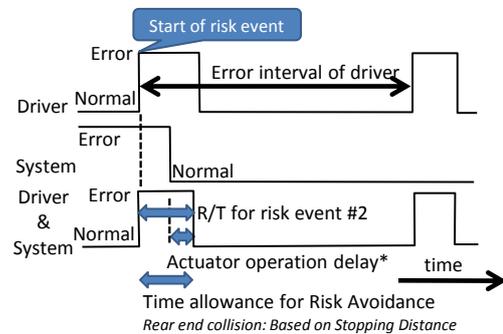
study, the actuator operation delay time was set to 0.3 s, which is defined in the ASV guidelines.



(a) Model in which the driver and system errors do not simultaneously occur.



(b) Model in which the driver and system errors simultaneously occur.



* NOTICE!
Actuator operation delay = 0.3s (ASV guideline)
If the R/T for risk event #2 is shorter and recovery of driver is earlier than the recovery of system, use this R/T#2 instead of Actuator operation delay.

(c) Model in which the period of driver and system errors partially overlap.

Fig.3 Simulation Model in which the vehicle is controlled by the driver and system.

3. Driving Simulator Experiment

3.1. Experiment and sub-task scenarios

Two scenarios, one wherein a rear-end collision occurs and the other wherein a lane deviation is induced, i.e., lane-deviation scenario, were used in the experiment environment simulated with the driving simulator. The simulator was set such that either one of

these scenarios was randomly used so that the experiment participants could not anticipate the upcoming scenario. Note that there were three conditions set in this experiment: “Driving a vehicle equipped with a system that can assist in longitudinal collision avoidance (ACC) or lateral direction collision avoidance, i.e., lane-deviation avoidance, (LKA),” “Driving a vehicle equipped with both systems (ACC + LKA),” and “Driving a vehicle not equipped with either of these systems.” Prior to the start of the experiment, the participants were informed of what type of driver assistance system was installed in their vehicle, and the simulator was set to use a collision or lane-deviation scenario. For example, when a vehicle was equipped with ACC, they were told that “the car you are going to drive has a function to keep the distance from your car to the car ahead of you constant. However, just like when you are driving your own car, you must press the brake pedal by yourself when you recognize the danger of a rear-end collision so that you can avoid an accident”.

Referring to a report (JSAE⁽⁶⁾, Aga et al. ⁽⁷⁾) wherein macro data analyzing real rear-end collisions and data in the event data recorder were used. The rear-end collision scenario used in the simulation is shown in Figure 4. This is one of the typical rear-end collision scenario on Japanese road. The deceleration time of the leading vehicle was randomly determined so that the experiment participants could not predict the timing. The participants experienced this driving five times for each driving assistance system. The scenario was such that if the participant did not start braking, the subject vehicle would collide with the leading vehicle 2.7 s after the leading vehicle started braking.

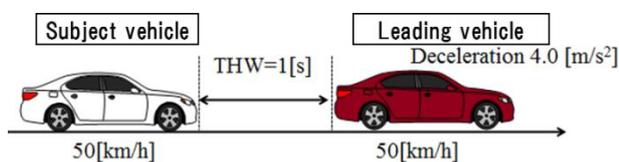


Fig. 4 Experimental scenario in the driving simulator to simulate a rear-end collision.

A highway in an urban area, which was in compliance with the Japanese road construction ordinance, was simulated and used to drive the vehicle in the lane-deviation scenario. This simulated highway was composed of a cornering section with easement curves and a straight section. The tight corner, whose minimum radius of curvature was 60 m ($R = 60$ m), was located on a part of the course. The radius of the tight corner was smaller than the radius of the other curvatures ($R = 80$ and 100 m); moreover, in this tight corner, a vehicle equipped with only LKA could not avoid lane deviation unless the driver initiated additional corrective steering. The location of this tight corner was different from one experiment to another so that the participants could not anticipate the location. A lane-deviation scenario that would induce a collision with a leading vehicle was used on the straight section of the course. The participants experienced this driving five times for each driver assistance system.

Noted that in the experiment with the driving simulator, the number of rear-end collisions and lane deviations was low because the duration of the drive was limited. To compensate for this limitation in the number of collisions and deviations, a subtask was

set up in the simulation to induce visual distractions for the experiment participant to simulate driving environments that included incidents such as imminent risk of collision. As the subtask in the experiment, the participants were asked to make entries into the car navigation system. They were required to enter the destination, as verbally instructed by the experimenter, into the car navigation system using Hiragana, i.e., phonetic characters in Japanese.

3.2. ACC and LKA operation pattern equipped with alarm systems

Two conditions—one wherein a vehicle was equipped with either one of the longitudinal and lateral driver-assistance systems and the other wherein a vehicle was equipped with both driver assistance systems—were used. Every participant in the experiment experienced a trial run prior to the actual experiment and each of these conditions was included in the trial scenario to allow the participants to understand the specific pattern of system operation.

The ADAS was designed so that the ACC could maintain an inter-vehicular distance equivalent to a THW of 1.0 s. The maximum deceleration controlled by the system was set to 3 m/s². Note that this ACC is equipped with Forward Collision Warning (FCW) which is similar to the system on the market. The FCW was designed so that an alarm was sounded when it would take 2.5 seconds to collide with the leading vehicle ($TTC = 2.5$ s).

The LKA was designed so that the corrective steering angle would minimize the lateral distance between the lane center and the point which is 1.0s-ahead of vehicle's center. The LKA was designed so that the vehicle could turn a corner without the driver's corrective steering and without deviating from the lane until the lateral acceleration reached 2.4 m/s². The system could make the vehicle turn corners on the course as long as the speed was 50 km/h and the radius of the turn was 80 m or more. Furthermore, when a participant steered the steering wheel with a torque larger than the system's steering torque while the LKA was operational, the participant's steering would override that of the system. Note that this LKA is equipped with Lane Departure Warning (LDW) which is similar to the system on the market. The LDW was designed so that an alarm was sounded when the lateral margin (distance) between the center of the tire before the lane deviation and the lane marker was 0.2 m or less.

To give the driver a sense of the imminent risk of collision, the FCW was designed to give an alarm as a series of beeps whose frequency was 2.4 KHz, period was 0.1 s, and duty ratio was 50%. These parameters of frequency, period, and duty ratio should provide drivers with a strong sense of urgency, as determined by an investigation conducted by authors prior to this experiment. The LDW was designed so that it could simulate the rumble strip sound (Suzuki et al.⁽⁸⁾) that is emitted when tires rotate on the bumpy (concave-convex surface) lane markers.

To facilitate a driver's comprehension of the system's operational status, the icons of ACC and LKA were displayed on the instrument panel. With these icons displayed on the panel, a driver should be able to easily understand the operational status of the longitudinal and lateral driver assistance systems or the status of just one of these systems.

3.3. Experiment participants

The experiment participants were 14 young males, with an average age of 22.4 and a standard deviation of 1.34 (22.4 ± 1.34). They all drove cars daily to commute to school or for recreation. One week prior to the experiment, a document explaining the content of the experiment was sent to each participant to obtain his consent. The participant joined the experiment after giving informed consent. Prior to conducting the experiment, its content was reviewed and approved by the Experiment Ethics Committee of Kagawa University.

3.4. Experimental results

3.4.1. Duration of the subtask

Figure 5 shows the frequency distribution of the subtask's duration, which is the time period required to enter the destination into the navigation system. Figure 5 shows that in a vehicle equipped with LKA or ACC, the subtask's duration tends to become longer than the duration when a vehicle is not equipped with the system. When a vehicle is equipped with both of the systems, this duration tends to become even longer than when a vehicle is equipped with just LKA or ACC. Although the subtask's duration was extended, the collision probability of the vehicle equipped with the multiple systems was not higher than that of the vehicle equipped with the single system, as described in Section 4.1. (Figures 7 and 8 and Tables 2 and 3).

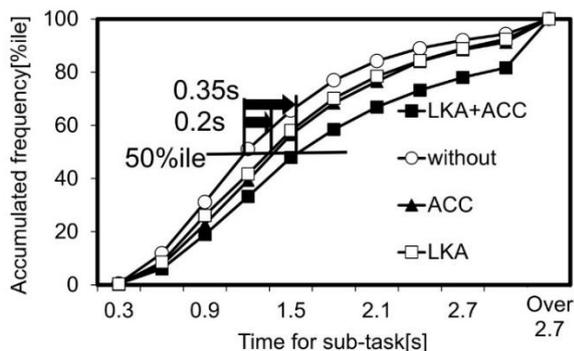


Fig. 5 Frequency distribution of the subtask's duration.

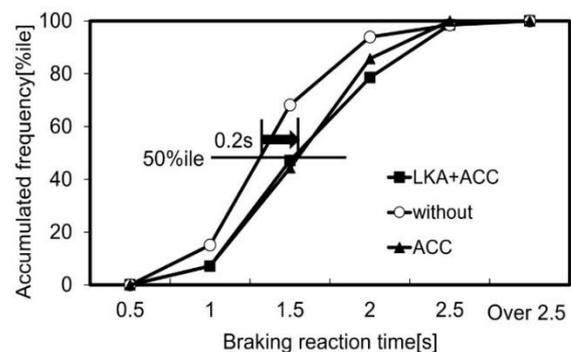
3.4.2. Braking reaction time

The braking reaction time of the experiment participants is shown in Figure 6(a). It can be observed that when the participants drove a vehicle equipped with ACC, the braking reaction time was longer than when they were driving a vehicle not equipped with the system. Moreover, when they drove a vehicle equipped with the driver assistance system in the lateral direction (LKA + ACC) the braking reaction time was longer than when they were driving a vehicle not equipped with the system. It appears that with the addition of the collision avoidance assistance feature, the drivers' braking reaction time was extended. In reality, the braking control of the system is initiated before the driver gains control; therefore, the collision probability tends to decrease, as shown in the simulations (Figures 7 and 8 and Tables 2 and 3). After the leading vehicle starts decelerating, TCC tends to become longer and the vehicle tends to be controlled more safely.

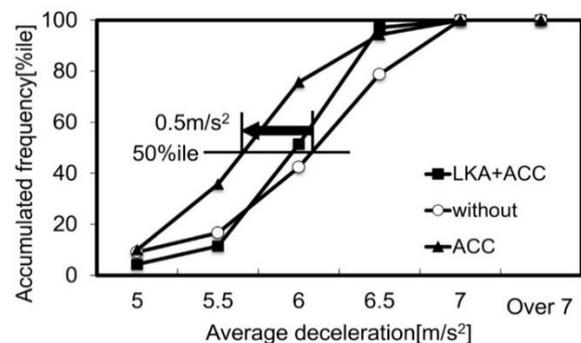
3.4.3. Average deceleration

The frequency distribution of the average deceleration of the subject vehicle is shown in Figure 6(b). Figure 6(b) shows that the average deceleration of a vehicle equipped with ACC is higher than that of a vehicle not equipped with the system ("without" in Figure 6). Conversely, the frequency distribution of the average deceleration of a vehicle additionally equipped with the lateral driver assistance system ("LKA + ACC" in Figure 6(b)) falls between the frequency distribution of the average deceleration of "without" and "ACC." The braking control of the system is initiated before the driver brakes with the help of a function that keeps the THW constant; consequently, the deceleration for collision avoidance can be kept low when the system was activated.

Feedback from participants after the completion of the experiment revealed that when the lateral driver-assistance function was added to the longitudinal driver assistance function, they could concentrate on the braking control because the lateral control maintained lane position, as supported by the lateral driver-assistance function. It appears that participants tended to press the brake pedal more strongly ("LKA + ACC" in Figure 6(b)).



(a) Frequency distribution of the braking reaction time.



(b) Frequency distribution of the average deceleration.

Fig. 6 Experimental braking-control behavior of the participants to avoid collisions with the leading vehicle.

4. Estimation of the Collision Probability with the Simulations

4.1. Collision mitigation effectiveness

The collision mitigation effectiveness of a vehicle equipped with ACC was analyzed in the following two cases: (A) a decrease of collisional probability when the system was normally operational and (B) an increase in collision probability due to the driver's overdependence on the system when it was difficult for the system to operate. The decrease in the collision probability (A)

and the increase in collision probability (B) were compared to evaluate the collision mitigation effectiveness of the system.

In the simulation, the duration of the time while it was difficult for the system to operate (system error state) and the interval of the system error state were assumed to be 30 ± 5 s and 300 ± 30 s, respectively, as shown in Table 1. This assumption was made to simulate an environment wherein the sensing of the situation around the vehicle with the system was relatively difficult.

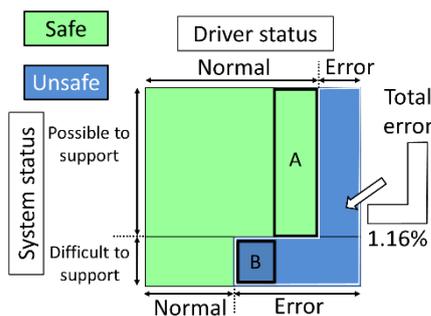
In the time-series reliability model shown in Figure 3, the state wherein the system normally operates (normal state) and that wherein it is difficult for the system to operate (error state) randomly occur. Furthermore, to obtain the collision probability, the simulation wherein the normal and error states were randomly generated. The collision probability of the normal state and that of the error state were sorted and are shown in Figure 7 and Table 2.

The collision probability is 40.3% when the system is not used under this condition, and the probability is reduced to as low as 1.16% when ACC is used. The decrease in the collision probability with the use of a system equivalent to zone A is 39.7%, and the probability increase with the use of a system equivalent to zone B is 0.557%. In this study, we are focusing on the risky driving situation.

When we estimate the collision probability on daily driving situations, it is necessary to multiply the probability of risky driving by these collision probabilities.



(a) Model used to estimate collision probability when the vehicle is not equipped with ACC.



(b) Model used to estimate collision probability when the vehicle is equipped with ACC.

Fig. 7 Effectiveness of ACC in decreasing collision probability.

Table 2 State variables related to collision Probability when the vehicle is equipped with ACC.

Benchmark of evaluation	Probability
Probability when the driver and system are operational (can control the vehicle)	98.4%
Probability when the driver and system are not operational (cannot control the vehicle)	1.62%
Collision probability when the system is not used	40.3%
Collision probability when the system is used	1.16%
Collision probability reduction with the introduction of system (A)	39.7%
Collision probability increase caused by system error (B)	0.557%

On the basis of Figure 8 and Table 3, we discuss the collision risk of a vehicle equipped with ACC and LKA. When a driver cannot normally control the vehicle (driver error state) and it is difficult for a system to operate (system error state), the collision risk is 1.62% in this simulation. When a system is not used, the collision probability is 40.3%, whereas it is lowered to 1.11% when ACC and LKA are used. The collision probability decrease with the use of a system equivalent to zone A is 39.7%, and the probability increase with the use of a system equivalent to zone B is 0.457%. The driving simulator experiment and the simulation analysis reported herein indicate that the positive effect of the addition of LKA to ACC is slightly larger than the positive effect of one system only (ACC).

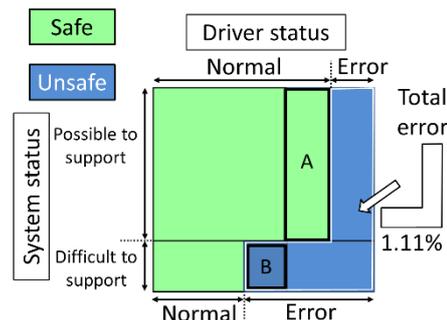


Fig. 8 Effectiveness of LKA in decreasing collision probability when LKA is installed in a vehicle equipped with ACC (LKA+ACC).

Table 3 State variables related to collision probability when LKA is installed in a vehicle equipped with ACC (LKA+ACC).

Benchmark of evaluation	Probability
Probability when the driver and system are operational (can control the vehicle)	98.4%
Probability when the driver and system are not operational (cannot control the vehicle)	1.62%
Collision probability when the system is not used	40.3%
Collision probability when the system is used	1.11%
Collision probability reduction with the introduction of system (A)	39.7%
Collision probability increase caused by system error (B)	0.457%

5. Discussion

5.1. Suppression of complacency with integrated ACC and LKA

When the two functions are installed in a vehicle, as discussed herein, a driver operated the subtask in addition to driving the vehicle more often than a driver with a vehicle equipped with a single function (Figure 5). However, the increase in the collision probability tends to remain unchanged (Figures 7 and 8 and Tables 2 and 3). The definition of the "Proper Dependence" must be discussed; however, this experiment revealed that a driver would not excessively depend on the driver-assistance system and that the dependence of the driver on the system would remain at the appropriate level.

There is a concern that the situation awareness, or "complacency" (Parasuraman et al.⁽⁹⁾, Moray et al.⁽¹⁰⁾), the level of the situation awareness might be lowered due to the driver's excessive reliance on enhanced levels of automation. However, from the above observations, it is understood that this level will not be lowered. This implies that since the drivers fully understood the "Limit of function" (Itoh⁽¹¹⁾), of the automation system and when the system can be function normally, the probability of collision and lane deviation does not increase. An understanding of the limit and the unchanged level of situational awareness are results of the briefing prior to the driving simulator experiment and pre-experiment trial run. During the briefing, the participants were informed of the functions of the driver assistance system under every experiment condition, and they could experience the collision and lane-deviation scenarios in the trail run. With the briefing and trial run, they could understand the "Limit of function." To check the lack of understanding on the limit of function in real traffic conditions, it is necessary to provide drivers with a "Chance of observation" (Inagaki⁽¹²⁾) so they can build their mental model of the driver-assistance systems functions.

5.2. Change of the safety level as human-machine system in long-term system usage

An issue that should be discussed is an evaluation of the behavior modification of drivers who have been using a system for a prolonged duration. The experimental study using a driving simulator was only conducted for a short duration. A safety assessment of driving-support functions ACC and LKA was conducted on the basis of the results of 14 drivers using these functions on a 5-km driving course. An evaluation of a driver using ACC and LKA in a driving simulator lasting several months may be difficult to achieve but is important. The braking behavior that prevents a rear-end collision may change when a driving-support function is used for a long duration. When ACC and LKA are used for a long duration, the incidence of visual distractions such as mobile phone usage or DVD viewing may increase. Moreover, drivers may easily fall into a state of low alertness. For these reasons, an evaluation over a longer duration may be needed. The following cases are the potential risks related to a driver's braking behavior during long-term usage of these driving-support systems:

- 1) In a situation where a system malfunctions, the takeover time, which is a driver's brake reaction time for avoiding a collision, may be prolonged. Because the takeover time for braking may be

prolonged, the collision risk may increase while using ACC and LKA. 2) Even if the system is operating normally, the override time, which refers to a driver's brake reaction time, may be prolonged. Because the override time may be prolonged, the collision risk may increase while using ACC and LKA.

6. Summary

In the driver simulator experiment, when a vehicle was equipped with the combined ACC and LKA systems, drivers tended to focus on the subtask (operation of car navigation system) more than if they were driving a vehicle equipped with either ACC or LKA. However, it was confirmed that the probability of a rear-end collision with the leading vehicle did not vary. When these two functions were combined, the level of the driving load mitigation was enhanced. Drivers tended to divert their attention to other tasks while driving; however, they could still take appropriate actions against risks such as rear-end collisions.

In both cases, when a vehicle was equipped only with ACC or with both ACC and LKA, the decrease in the collision probability for the condition where the system can assist the driver, i.e., the system's normal state, was confirmed to be much higher than the increase in collision probability when it was difficult for the system to assist the driver, i.e., system error state. This was confirmed by the simulation analysis that used the driver behavior database obtained by the driving simulator experiment. When a driver uses a vehicle depending on the system, there is a concern that the collision probability will be higher than the probability when the vehicle is not equipped with the system when it is difficult for the system to assist the driver. However, the decrease of in the risk with the system, which called the "positive effect," is far greater than the increase in the risk, called the "negative effect."

As a prerequisite for these conclusions, there must be a "Chance of observation" provided to drivers so that they can build a mental model of the driver assistance system and how it functions. To enhance the automation level of the autonomous drive system in its final design goal, an interface to enable the proper risk communications between the system and the driver will be developed, and drivers will be trained with repeated trial runs so that they can fully understand the systems functional limits. This is critical to prevent drivers from lowering their situational awareness due to an excessive dependence on the system.

This study was carried out as a part of 5th ASV promotion project by Engineering Policy Division, Road Transport Bureau, Ministry of Land, Infrastructure, Transport and Tourism.

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