A STUDY ON THE ONSET TIMING OF COLLISION AVOIDANCE ASSISTANCE SYSTEM FOR MINIMIZING OVER-RELIANCE ON THE SYSTEM

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ABSTRACT

We analyzed drivers' braking behavior to minimize over-dependence on the system in the design of the Forward Collision Avoidance Assistance System. There are various factors that influence over-dependence on the system. We focused on the braking algorithm to minimize interference between driver operation and system actuation in this study. It was proven that all subjects initiated the braking operation in advance of system actuation when the system was actuated at a Time to Collision of 1.7s or less and when the car approached a stationary obstacle at 60km/h. We propose that Time to Collision is an effective state variable for analyzing the dependence level on the system, and that a Time to Collision setting of less than 1.7s is optimal for the onset timing to minimize over-dependence on the system.

INTRODUCTION

Several kinds of driving assistance systems are proposed in this project to improve traffic safety by utilizing state-of-the-art technologies. Forward collision avoidance assistance systems [1) 2) 3) 4)] are in the development phase and are examples of driving assistance systems aimed at supporting accident avoidance. The purposes of this system are to avoid collisions and reduce the damage from collisions. Putting these systems into practical use is expected to result in effective accident avoidance and/or damage reduction in collisions. However, over-dependence on the system could occur in practical use if the system is not properly designed. This problem will arise if the driver does not initiate sufficient braking when the car is at risk of collision with a preceding vehicle. This "risk-taking behavior" is a deviation from the concept of the driving-assistance system. Therefore, an appropriate system design that considers human interaction is necessary to avoid excessive dependence on the system. The purpose of this study is to clarify the requirements for a better system design that takes into account human participation to minimize excessive dependence on the driving assistance system.

There are various factors that influence dependence on the system. We believe that the level of interference between driver operation and system actuation, the level of discomfort from the actuation behavior of the system, and system actuation reliability will affect the driver's dependence on the system. We focused on the braking algorithm in this study to minimize the interference between driver operation and system actuation. For example, it is possible that the driver may not brake sufficiently when the start timing of the system braking control is early (when the level of interaction between driver operation and system actuation is high). However, the driver may brake sufficiently when the start timing of the braking control is after the driver's

braking operation (when the level of interaction between driver operation and system actuation is low). We must avoid situations in which the driver fails the essential driving task. Therefore, it is important to clarify the start timing of braking control by the system so the driver does not depend excessively on the system.

We conducted an experimental study with the driving simulator at Japan Automobile Research Institute (JARI), and investigated behavioral changes relevant to braking manipulation when the start timing of braking control was varied. These experimental results enabled us to establish the start timing of braking control in such a way that the driver does not exhibit behavioral changes that indicate over-dependence on the system. We focused primarily on the driver's behavior during the braking operation in this study, and analyzed methods of braking control by the system that do not interfere with driver operation. The following two requirements are important for preventing interference between the driver and the system during braking operation.

a) *Initiation of braking control by the driver*

The driver initiates braking operation before braking control by the system.

b) *Collision avoidance by the driver*

The driver performs braking when the Time to Collision becomes minimum, indicating that the danger of the collision is greatest.

EXPERIMENTAL METHOD

We set up experimental scenarios in which the vehicle approached a stationary obstacle at 60km/h in the virtual space of a driving simulator. This driving scenario simulated a situation in which the forward obstacle collision avoidance assistance system would operate. The drivers' braking behavior was observed when the start timing of braking control was varied. Both the braking control function and the forward vehicle collision warning function would be installed in the system in the actual system design. Only the braking control function, without warnings, was set up in this study in order to analyze the relation between the start timing of braking control by the system and the drivers' braking behavior.

Apparatus

The JARI dynamic driving simulator was used in this study. It consists of five subsystems: a computer system with the simulation model, a hydraulic moving base system, a visual system, a sound system, and a temperature regulating system. The high-performance computer graphics have a short time delay of less than 60ms. The simulated background noise in the car corresponds to that in modern passenger cars.

Driving Scenario in the Experiments

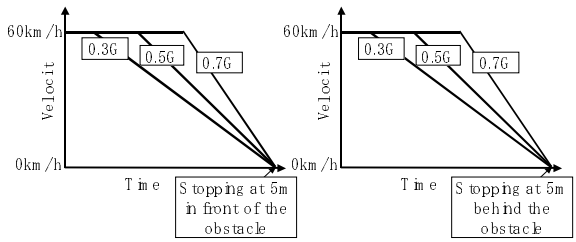
We constructed two straight lanes that simulated the Japanese expressway in the space of virtual reality. Clumps of vegetation were placed beside the road, each lane of which was 3.5 m wide. A cluster of trees following the road shoulder were arranged on the left side, and a curb and shrubbery were arranged following the road shoulder on the right side. The operator of driving simulator instructed the subjects to drive on the left side of the lane. A forward view from the driver's line of sight is provided in **Figure 1**.

Braking Control Algorithm by the System

The braking control pattern during system actuation is shown in **Figure 2**. The control pattern when the goal stopping position was in place in front of the obstacle (for avoiding the collision) is illustrated in **Figure 2(a)**, and that when the goal stopping position

was in place behind the obstacle is shown in **Figure 2(b)**. The car will collide with the obstacle when the goal stopping position is set behind the obstacle if the driver does not perform braking operation. Three deceleration levels, 0.3G (2.9m/s^2), 0.5G (4.9m/s^2), and 0.7G (6.9m/s^2), were configured for the vehicle for use during system actuation. Two positions, five meters forward of the obstacle and five meters behind the obstacle, were set up as a target stopping points.

Figure 1 Forward view from the driver's line of sight



(a) (b)

Figure 2 Braking control pattern during system actuation

Test Subjects

Twelve male drivers and thirteen female drivers, a total of twenty-five drivers (aged 28 – 49 years, average age of 35.8 years, standard deviation of the age was 6.4 years) participated in this study. All drivers were experienced, with a total driving distance of more than 5,000 km per year. These subjects were chosen from the general population and were not JARI test drivers.

Experimental Procedure

We asked the subjects to drive the simulator to familiarize themselves with its motion to commence our investigation of braking behaviors. A driver repeated the braking operation with an initial constant velocity of 60 km/h during this test drive. The duration of the test drive was 15 minutes.

We asked the subjects to learn the braking maneuver of the system after the test drive. The experiment operator first explained the details of the action of the braking maneuver to the subjects. The operator then asked the subjects to familiarize themselves with the onset timing of braking assistance when the system was activated. The subjects underwent this trial three times. The drivers were instructed not to perform braking and to experience system actuation in these trials, to better understand the function of braking control by the system. The experiment operator completed these trials by confirming that the subjects sufficiently understood the braking maneuvers of the system.

The primary experimental study to investigate the drivers' braking operation was conducted after all drivers had completed the trials to learn the system function. Six different braking maneuvers, including three levels of deceleration and two levels of stopping point, were completely randomized in this primary experimental study in order to minimize the learning effect. The subjects were instructed to use the forward collision avoidance assistance system during this trial if they wanted to do so. The drivers' behavior without the system was investigated in addition to the driver's behavior when the system is equipped to analyze the difference in driver operation between the two conditions.

EXPERIMENTAL RESULTS

Subjective Evaluations

We prepared two subjective evaluations for the test subjects. The average and standard deviation of the subjective evaluations of the "Dependence level on the system" and "Change of driver's braking operation during system actuation" are shown in **Figure 3**.

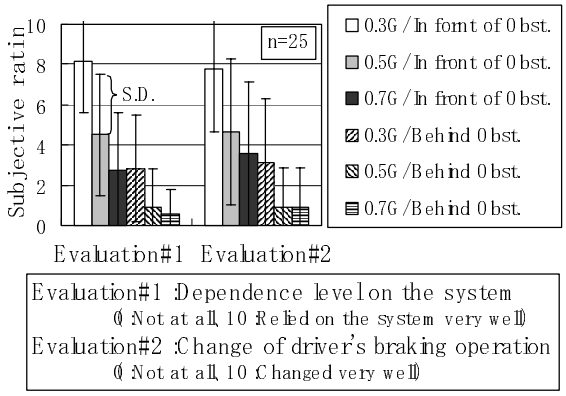


Figure 3 Results of subjective evaluations

The results in the condition of "0.3G / Stopping in front of the obstacle," depicted on the left side of the figure, suggest that the dependence level on the system was high and also suggest that the drivers were aware of the change in their own braking operation. In contrast, the results in the conditions of "0.5G / Stopping behind the obstacle" and "0.7G / Stopping behind the obstacle" (first and second from the right side of the figure) suggest that dependence on the system and the change in braking operation were extremely low. The subjective evaluation result clearly fluctuated substantially in the different braking control patterns. The degree of the dependence on the system was proven to be high during braking control when the system perfectly avoided collision with the obstruction (when the goal stopping position was set in front of the obstacle), compared with trials when the goal stopping position was set behind the obstacle.

Classification of Drivers' Braking Behavior

The drivers' braking behavior during the experiment was classified into four types; the frequency of each type is shown in **Figure 4**. The definitions of the classification of drivers' braking behaviors are listed below.

(a) Only manual control by the driver (Driver only)

Only the driver manipulated the braking; the system was not actuated.

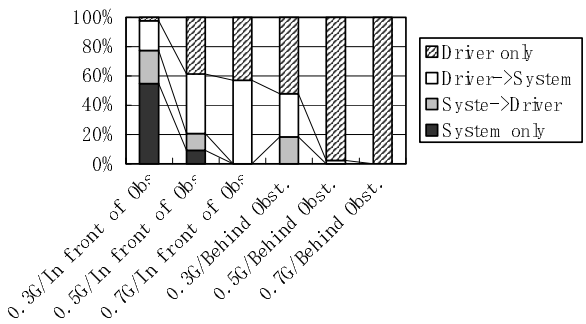


Figure 4 The driver's braking behavior

(b) Precedence of manual control (Driver→System)

The driver's braking behavior was predominant, and the system was subsequently actuated.

(c) Precedence of system control (System→Driver)

System actuation was predominant, and the driver manipulated the braking later.

(d) Only automatic control by the system

(System only)

Only the system controlled the braking; the driver did not manipulate the braking at all.

The results in the condition of "0.7G / Stopping in front of the obstacle" (third from the left), "0.5G / stopping behind the obstacle" (second from the right) and "0.7G / stopping behind the obstacle" (right side) suggest that the overall frequency, including "Only manual control" and "Precedence of manual control," was 100%. This indicates that every subject

manipulated the braking earlier than system actuation. Thus, it can be stated that no interference between the system and the driver was observed in these conditions. The frequency of "Only automatic control by the system" in the condition of "0.3G / stopping in front of the obstacle" (first from the left) was greater than 50%, and behavioral change was observed in the driver. This indicates that the driver and the system interacted and that the dependence level on the system was high in comparison with the above-mentioned conditions, such as 0.7G / Stopping behind the obstacle. An more detailed analysis of the relation between the start timing of braking control and these drivers behavior changes will be described below.

Average Braking Force by the Drivers

Average braking force by the subjects is provided in **Figure 5**. The braking maneuvers in conditions of "0.3G / Stopping in front of the obstacle" (first from the left) and "0.5G / Stopping in front of the obstacle" (second from the left) indicate that some subjects did not apply the brakes at all. It appears that the drivers in these conditions were completely dependent on the system and did not operate the brakes. The average braking force when the drivers performed braking control was analyzed, with the exception of those results when the drivers did not exert any braking control. While only the results when the driver performed braking control were analyzed, the results in the condition of "0.3G / Stopping in front of the obstacle" suggested that the braking force by the subject was lower than in the other braking patterns. The behavioral change regarding braking manipulation is evidently one index that suggests the level of dependence on the system.

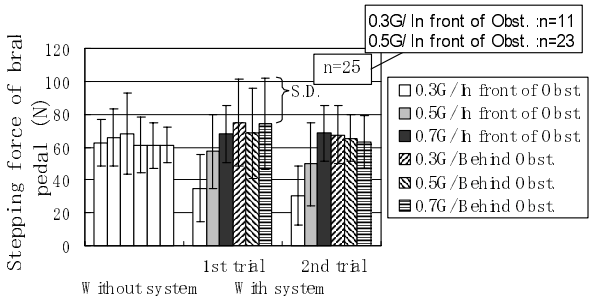


Figure 5 Stepping force of braking pedal in each condition

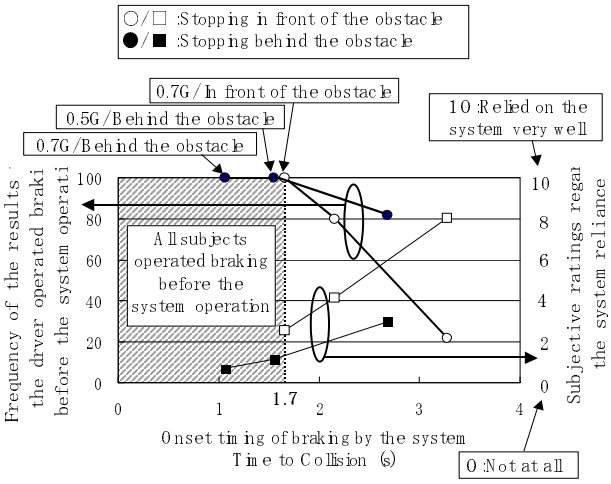


Figure 6 Relation between the start timing of braking control and the frequency with which the subjects started the braking operation before system actuation

Condition in which the Driver Initiates the Braking Operation before Braking Control by the System

We analyzed the relation between the start timing of braking control by the system and the dependence level on the system (average value of a subjective evaluation) and also analyzed the relation between the start timing of the braking control and the frequency with which the subjects started the braking operation before system actuation. The results are depicted in **Figure 6** with respect to the target stopping point and the level of deceleration. The horizontal axis indicates the start timing of braking control by the system in terms of the "Time to

Collision." This state variable, the Time to Collision, can be determined by dividing the relative distance between the car and obstacle by the relative velocity between the car and obstacle.

The frequency with which the subjects operated the brakes earlier than the system was lower in the braking algorithm in which the stopping point was set in front of the obstacle compared with the braking algorithm in which the stopping point was set behind the obstacle. An increase of the dependence level on the system was also noted when the stopping point was set in front of the obstacle

The relationship between the control start timing of the system and the driver's braking behavior was then examined by using Time to Collision as an index. While the stopping position (in front of the obstacle / behind the obstacle) may affect the level of dependence, all subjects performed the braking operation in advance of system actuation when the start timing of the braking control by the system was shorter than 1.7s with respect to the Time to Collision (oblique line in the figure; 0.7 G / Stopping in front of the obstacle, 0.5G / Stopping behind the obstacle, 0.7 G / Stopping behind the obstacle). The "goal stopping position" and "deceleration level during system actuation" were changed as experimental conditions in this study. However, it is clear that the start timing of system actuation indicated by the Time to Collision is one index for evaluating the level of the operation interference between the system and the driver. The following condition is satisfied when the Time to Collision as the start timing of the system braking control is shorter than 1.7s.

The driver initiates the braking operation in advance of braking control by the system.

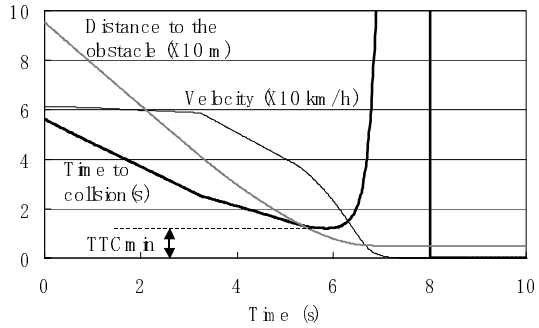


Figure 7 Fluctuation of Time to Collision during driver's braking

Condition in which the Driver Performs Braking for Collision Avoidance

The fluctuation of Time to Collision during the drivers' braking operation is provided in **Figure 7**. It became apparent that Time to Collision never fell below a certain value, indicated as TTCmin in the figure. Evidently all drivers felt that the risk of collision was extremely high when Time to Collision became less than TTCmin, and all drivers controlled their braking manipulation to maintain the condition that Time to Collision never fell below TTCmin. This minimum value of Time to Collision was 0.84s in all trials in this study. Therefore, it is possible to assume that the drivers will personally manipulate the braking operation to avoid a collision if we set the braking algorithm (the deceleration level and stopping position) so that Time to Collision becomes less than 0.84s during braking control by the system. These results satisfy the following condition when Time to Collision during brake actuation is shorter than 0.84s.

The driver performs braking when Time to Collision becomes minimum, indicating that the danger of collision is greatest.

BRAKING CONTROL ALGORITHM TO PREVENT INTERFERENCE BETWEEN THE DRIVER AND THE SYSTEM

We examined the design method of the braking algorithm to prevent interference between braking by the driver and braking control by the system. We focused on the driver's braking behavior during the start of braking and avoidance of collision. We found that the following two requirements are important for minimizing operation interference between the driver and the system and over-dependence on the system.

a) The driver starts the braking operation in advance of braking control by the system.
b) The driver performs braking when the Time to Collision becomes minimum, indicating that the danger of the collision is greatest.

The reason we chose these two requirements to avoid interference between manipulation by the driver and system actuation is illustrated in **Figure 8**. For example, the system will be activated when the vehicle velocity overruns the system's braking control velocity even if the driver's manipulation is in advance of system actuation because the driver's braking is not sufficient. It is therefore important for the driver to exert pressure on the brake pedal at certain timing to avoid collision.

We chose the time when Time to Collision becomes minimum, indicating that the risk of the collision is highest, as the time when the driver should depress the brake pedal. We consider that pressure on the brake pedal at this time by the driver is important to minimize the level of dependence on the system, since this driver activity signifies that the driver will avoid collision by his/her own operation when the risk of collision is greatest.

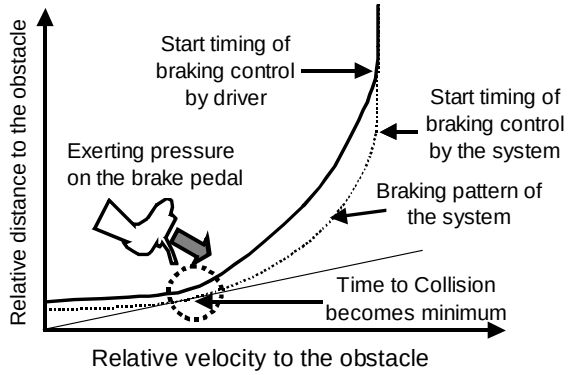


Figure 8 Requirements to avoid interference between the driver and the system

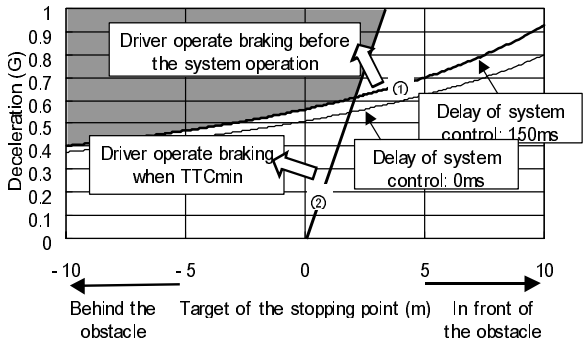


Figure 9 Design range of a system to avoid interference between driver operation and system actuation

We examined the design range of a system that can simultaneously satisfy the above two conditions based on the driver's behavior in this study. The results are revealed in **Figure 9**. The horizontal axis indicates the goal stopping position, and the vertical axis represents the deceleration level of the system. The Time to Collision at the start of braking control by the system will be less than 1.7s when the deceleration and stopping point are designed in a region above curved line 1. Braking by the driver comes before system actuation under this condition, which satisfies the above condition a). We used 150ms as the process delay time of braking control in our analysis of the design range of the system, since the kinetic characteristics of the system were constructed in the JARI driving

simulator. As a reference, curved line 1 is also shown when the process delay time to braking actuation was 0s .

The Time to Collision during braking control by the system will be shorter than 0.84s in situations when the deceleration and stopping position are designed in the region to the upper left of line 2. The aforementioned study indicated that every subject personally performed braking when Time to Collision became shorter than 0.84s during system actuation. Therefore, it can be assumed that drivers will manipulate braking operation for collision avoidance when the deceleration and stopping position are designed in this region.

These survey results clarify that the driver initiates the braking operation in advance of the system when the system is designed in the region shown in gray on the left in the figure, and that the driver will perform braking for collision avoidance when the risk of collision is greatest. It is evident that operation interference between the driver and the system does not occur when the system is designed in this region, and the driver's dependence on the system will be minimal. An example of the system design satisfying these conditions is described below.

Deceleration: 0.5G

Stopping position: -5m (5m behind the obstacle)

CONCLUSIONS

Insight into a better system design to avoid operating interference between the driver and the system and to avoid excessive dependence on forward collision avoidance assistance systems was obtained in this study. The primary results derived from this investigation are described below.

Investigation of Driver Behavior for Collision Avoidance

a) All subjects initiated braking before system actuation when the system was actuated at a Time to Collision of 1.7s or less, under conditions in which the car approached a stationary obstruction at 60km/h.

b) It appeared that all subjects performed braking during collision avoidance in such a way that Time to Collision remained above 0.84s.

Functional Requirements for Preventing Operation Interference between Driver Operation and System Actuation

a) We clarified the design method of the braking algorithm to minimize interference between braking by the driver and braking control by the system. We focused on the driver's behavior during the initiation of braking and collision avoidance. We consider the following two requirements to be important for minimizing interference between the driver and the system, and over-dependence on the system.

   The driver initiates braking in advance of the braking control start timing by the system.

   The driver performs braking when the Time to Collision becomes minimum, indicating that the danger of collision is greatest.

b) The above requirements will be satisfied when we design a system based on the following conditions.

   The braking control start timing indicated by Time to Collision should be set at 1.7s or less. The minimum Time to Collision during braking control by the system should be less than 0.84 s.

Urban district driving was assumed in this study, and conditions in which the vehicle approaches an obstacle at a speed of 60km/h were arranged. It was proven that no interference between the driver and the system was generated if the start timing of the system actuation was set at a Time to Collision of less than 1.7 seconds. However, the conditions to minimize interference between the driver and the system will probably be different when the vehicle velocity is varied. We will conduct investigations when the vehicle velocity differs in the next step of this study.

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