

**Research
Report****A Study of a Personally Adaptive Driving Support System
Using a Driving Simulator**Sueharu Nagiri, Yasushi Amano, Katsuhiko Fukui, Shun'ichi Doi

Abstract

The social damage caused by road traffic accidents is enormous, and governments and companies around the world have devised and implemented countermeasures to reduce such accidents. Among these, driving support systems are being researched and developed as an accident-preventing measure. Driving Simulators (DS) are an effective tool for developing such a driving support system and evaluating new

Human Machine Interfaces (HMI).

This paper describes the newly developed Toyota Research Driving Simulator (TRDS) and presents the results of analyzing the driving characteristic data that we accumulated. In addition, we present some results obtained with the Personally Adaptive Driving Support System (PADSS).

Keywords

Road traffic accident, Driving support, Human-machine interface, Driving simulator, Warning

1. Introduction

In Japan, while the number of fatalities caused by road traffic accidents has been falling slightly, the number of actual accidents and resulting injuries has been increasing year-on-year. Many driving support systems are being developed in an attempt to reduce the number of road traffic accidents.^{1, 2)} Such systems often feature thresholds that are set based on the skills of an average driver. There is a concern, however, that such an "average-level" setting is not appropriate for providing driving support to each and every driver. So, we are studying a "Personally Adaptive Driving Support System" (PADSS) that can be tailored to individual drivers. To make such a system work, both an investigation of individual drivers' driving characteristics and a related database are necessary. To this end, a driving simulator is an excellent tool for creating a database for studying the effects of a driving support system.

In this paper, we discuss the introduction of the Toyota Research Driving Simulator (TRDS) and its use as a tool for developing the PADSS system. We also discuss the results of some of our experiments.

2. Driving simulator

2.1 System construction

The TRDS installed at the Toyota Central Research and Development Labs. is shown in **Fig. 1**. The blue shell in the six degree-of-freedom (6 DOF) motion system accommodates the driving cockpit. The 6 DOF motion system is able to move longitudinally by ± 4 m. The configuration of the TRDS is shown



Fig. 1 Appearance of TRDS (Toyota Research Driving Simulator).

in **Fig. 2**.

This TRDS has five components: the common system, feel servo system, motion system, visual system, and support system. The main part of the common system performs vehicle dynamics calculations by using the CarSim real-time simulation software. The vehicle dynamics for nineteen degrees-of-freedom are calculated at 1 ms intervals, and the results are used to draw a scene and to generate the acceleration forces experienced by the driver. The steering reaction torque is the most important feature of the driving simulator. The feel servo system generates this steering reaction torque by using a DC electric servo motor. The torque applied by this motor is based on the slip angle of the front wheels and the steering angle. The motion and visual systems are described in the following section. The support system has three functions. The first records data such as the driver's actions and the vehicle velocity. This data includes the driver's eye movements. The second judges whether the vehicle will collide with the vehicle it front. The third warns the driver of the possibility of a rear-end collision.

2.2 Motion system

The motion system reproduces the forces that occur as a result of changes in the vehicle's motion, such as steering or braking. In the case of an actual vehicle, free longitudinal and lateral movement is possible on the roadway. The driving simulator,

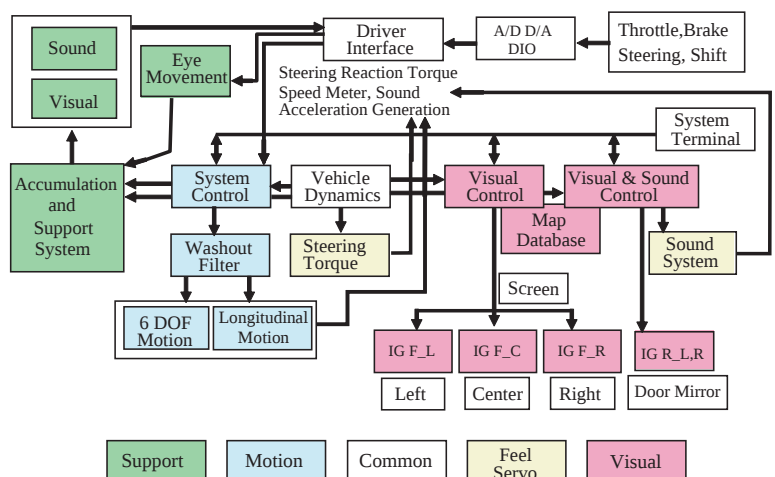


Fig. 2 System construction of TRDS.

however, can work only within a limited range of motion. The specifications of the TRDS that we developed for PADSS are listed in **Table 1**. The TRDS motion system supports 6 DOF motion and longitudinal motion. The range of the longitudinal motion is ± 4 m. The 6 DOF motion is realized by adopting a link mechanism that is mounted on the longitudinal motion base. The vehicle acceleration used to move these devices is calculated by the CarSim software. The calculated vehicle accelerations are fed to the motion generator to imitate the actual motion of a vehicle.

2.3 Visual system

The specifications of the TRDS visual system are listed in **Table 2**. A computer graphics image from

the image generator (IG) is projected by a liquid-crystal projector onto three flat screens installed 1.4 m ahead of the driver. **Figure 3** shows a scene depicting an interchange, as stored in the visual database. **Figure 4** shows a street scene in a town, as it would be seen by the driver. The creation of such a scenario is a very important part of a test using the driving simulator. The TRDS is capable of projecting 32 other moving objects, such as vehicles and pedestrians. The movements of these objects are generated by a scenario editor, as shown in **Fig. 5**. Figure 5(a) shows the route taken by a certain object, while Fig. 5(b) shows some possible vehicle routes in the vicinity of an intersection. The way that an object will appear is set by assigning a speed to an arbitrary point on the road. The movement of these objects can be set in either of two ways. The first moves regardless of the movement of the driver's vehicle, while the second starts to move only when the driver enters a certain event range.

Table 1 Motion system specifications of TRDS.

DOF	6 (Serge, Sway, Heave, Roll, Pitch, Yaw) + 1 (Longitudinal)	
Type	Link mechanism + Rail	
Controller	Assembled PC	
Range	Disp.	Serge: ± 0.35 m Sway: ± 0.35 m Heave: ± 0.35 m Roll: ± 22 deg Pitch: ± 22 deg Yaw: ± 22 deg Longitudinal: ± 4 m
	Acc.	Serge: 4.9m/s^2 Sway: 4.9m/s^2 Heave: 4.9m/s^2 Roll: 160deg/s^2 Pitch: 160deg/s^2 Yaw: 160deg/s^2 Longitudinal: 4.9m/s^2

Table 2 Visual system specifications of TRDS.

Image generator	Lockheed martin : REAL 3D PRO-1410 Ability : 1M polygons/s	
Controller	Assembled PC	
Projector	Front	Liquid crystal projector (3ch ; Left, Center, Right)
	Back	Liquid crystal display (2ch ; Left, Right)
FOV (Field of view)	Front	Horizontal: ± 75 deg Vertical: $+25$ deg ~ -13 deg
	Back	Angle to view in a door mirror
Resolution	Front	Front view: XGA (1024*768 pixels)
	Back	Back view: VGA (640*480 pixels)
Frequency	60 Hz	
Time delay	50 $\sim$ 60 ms	



Fig. 3 Visual image of the database.



Fig. 4 Driving scene in town area.

3. Driving data analysis

3.1 Experimental method and data logging

The driving scenario used for accumulating the driver's braking patterns was a course to a destination in a parking lot of town EAST, via the expressway, from a departure point in a parking lot of the neighboring town WEST. After the driver starts away, the vehicle in front leads him or her to the destination. The distance is about 18 km, and the journey takes around 25 minutes. Of course, another 32 vehicles, in addition to the driver's own vehicle, are also moving in the area. The twelve subjects consisted of ten men and two women.

The TRDS records the own vehicle dynamics data, as well as that for the other vehicles. Furthermore,

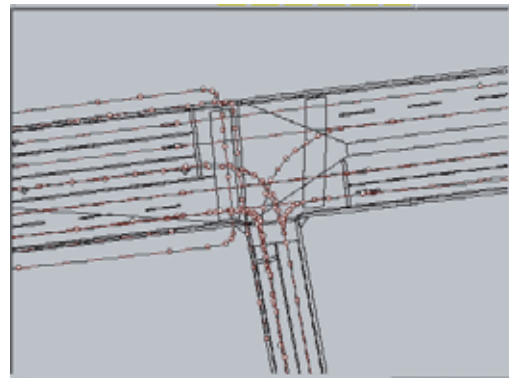
an identification number (ID) is set for all roads and intersections, and the road ID and the distance to the next intersection are recorded. Based on this data, the system judges whether a collision with the vehicle in front is imminent. If a collision is foreseen, a warning is issued.

3.2 Results of analyzing braking patterns

The measured values for vehicle velocity and deceleration for ten journeys are listed in **Fig. 6**. Subject EK brakes consistently, starts to brake at the same points, and applies very similar decelerations for each of the ten journeys. The braking start point and deceleration are quite different for subject YT, however. As shown in Fig. 6, the braking patterns are different for each subject. **Figure 7(a)** shows the average and standard deviation of the deceleration at

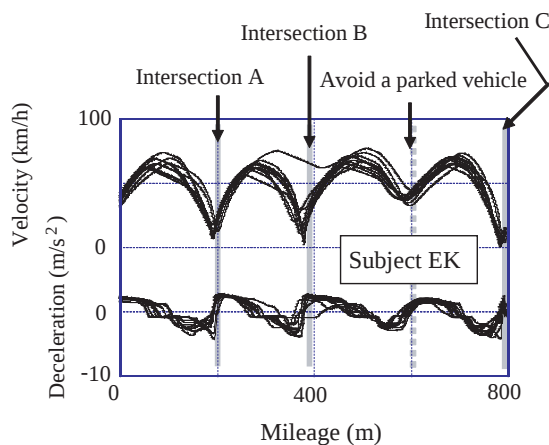


(a) Example of the whole route

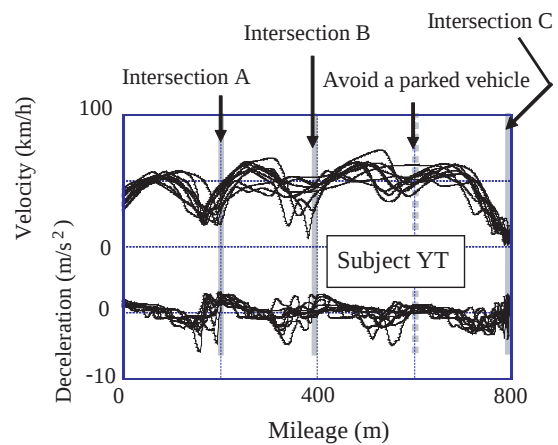


(b) Some routes in an intersection neighborhood

Fig. 5 Example of drive route by the scenario editor.



(a) A driver who brakes in same driving



(b) A driver who differently brakes in each driving

Fig. 6 Braking operations at some intersections.

an intersection, and Fig. 7(b) shows the same statistics for two subjects at eight different intersections. From these figures, we can see that the magnitude and standard deviation of the deceleration differ for each subject and place. These results point to the need for PADSS.

4. Personally adaptive driving support system (PADSS)

4.1 System concepts

A driving support system detects an error in the "recognition", "judgment", or "operation" of a driver and presents either a sound or a signal if the error is judged to be dangerous.^{3, 4)} Also, the system takes over control of the vehicle if the driver is unable to avoid a collision. To date, such systems have often issued warnings and exercised control based on the driving characteristics of an average driver. Because of the wide variation in braking patterns, as shown in Fig. 7(a), however, it is thought that the issue of warnings based on mean values like this would lead to a sense of incongruity. Therefore, we first determine the time needed for the driver to move his/her foot from the gas pedal to the brake (braking reaction time), as well as the amount of braking applied by each driver. As a result, a warning would be issued at an appropriate level if he/she deviated from this accumulated data. The concept of PADSS is the avoidance of a dangerous situation such as a rear-end collision in the event of a deviation from the normal braking pattern, as based on the accumulated data for each driver.

4.2 Personal adaptation method

In this section, we describe our experiments for determining a method of issuing a warning based on accumulated braking data. Our goal was to warn the driver of the danger of a rear-end collision. Whether a warning is issued is determined using the equation shown in Fig. 8. The own vehicle velocity V , the velocity of the vehicle in front V_f , the deceleration of the vehicle in front α_f , and the distance to the vehicle in front D , were measured during the experiment. The braking reaction time T and subject's deceleration α were extracted from the braking database for each subject, and were set in real time. The methods used to set the braking reaction time T and the deceleration α are shown in

Equation of the rear-end collision judgment

$$D \leq [VT + \frac{V^2}{2\alpha} - \frac{V_f^2}{2\alpha_f} + d_0]$$

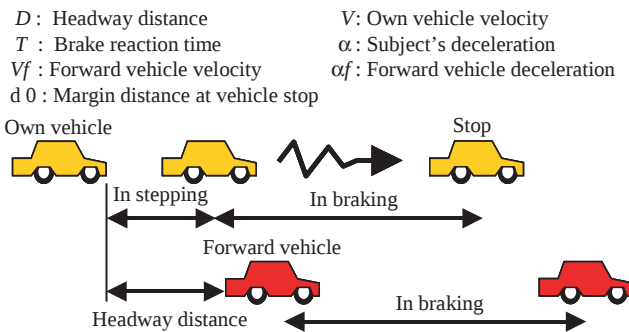
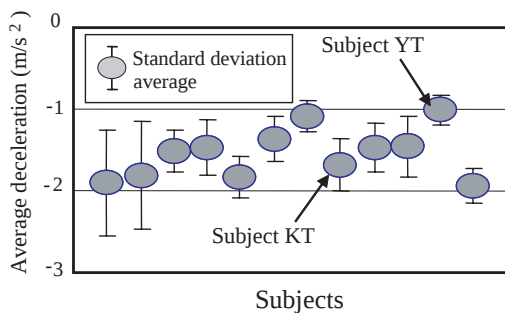
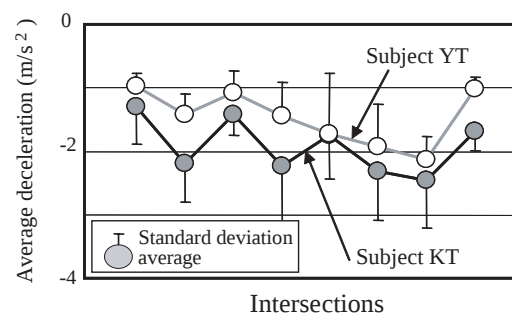


Fig. 8 Rear-end collision judgment.



(a) The difference by each subject



(b) The difference by each intersection

Fig. 7 Average decelerations.

Fig. 9. For these parameters, the 10% tile value of the extracted data is set for each driver. The 10% tile value is set in those situations where there would appear to be a deviation from the normal braking pattern of the subject. In this way, our PADSS can detect a delay in the recognition of an individual driver's judgment and/or braking pattern.

We constructed the system shown in **Fig. 10** to aid in the development of a warning algorithm in PADSS. The incorporation of the collision judgment algorithm into PADSS, and confirming whether the parameter can be used to decide a warning timing, can be executed in real time using a PC in the analysis room and using the recorded data. The development of this algorithm allows the driver to

recognize his/her own vehicle's movement and be aware of the output of visual warnings.

Based on the accumulated braking database, the effect of PADSS was examined by using it to issue warnings in some dangerous situations. The driving course used was very similar to that used to investigate each individual driver's braking. The other 32 vehicles are again moving in the same area, but a variety of dangerous situations are set. These dangerous situations include the pulling-out of a parked vehicle, and the sudden left turn of the vehicle in front without signaling. We used the same twelve subjects. The experiment was based on three journeys. To examine the need to issue a warning, a subjective evaluation was executed at the same time. The subjective evaluation used the four levels shown in **Table 3**.

4.3 Warning output results

The warning output frequency for the three journeys is shown in **Fig. 11**. The number of

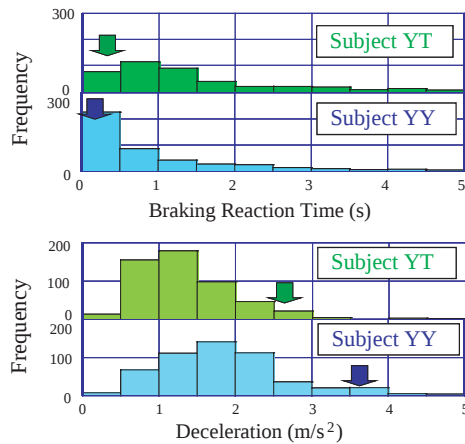


Fig. 9 Setting method of the parameter for each driver.

Table 3 Subjective evaluations for the warning.

Level	Subjective evaluation
1	Unnecessary
2	Slightly necessary
3	Necessary
4	Very necessary

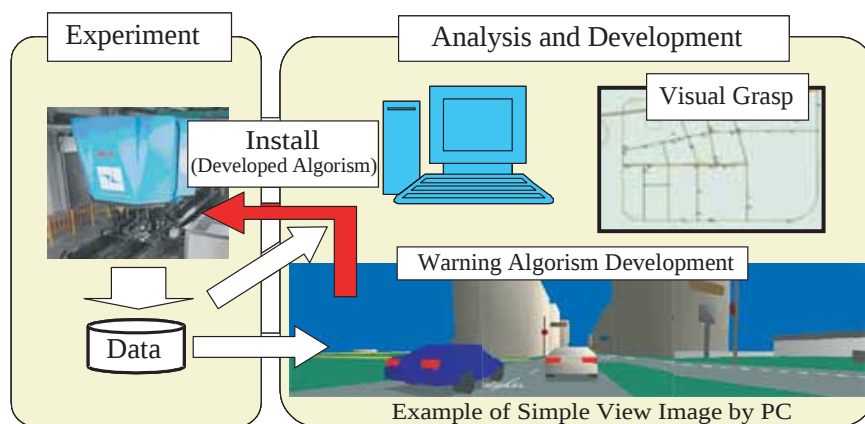


Fig. 10 Constructed system for experiment data analysis and warning algorithm development.

warnings differs considerably depending on the subject, ranging from 2 to 44. Subject HM, who caused the greatest number of warnings to be output, was issued about fifteen warnings for each journey. The relationship between the warning frequency and the driving characteristics is discussed below. **Figure 12** shows the frequency distribution and the cumulative frequency of the average deceleration for two subjects. These subjects are HK with seven warnings, and HM with 44 warnings; they are of similar age and the same gender. From Fig. 12, we cannot see any difference in the intensity of their braking. Therefore, it would seem that, for both subjects, almost the same value is set for the deceleration α , shown in Fig. 8. We examined the braking reaction time T is the same way and, essentially, the same values were found for both

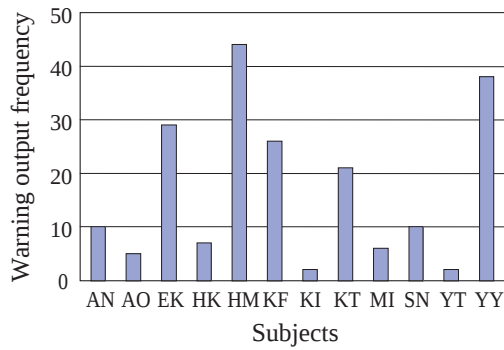
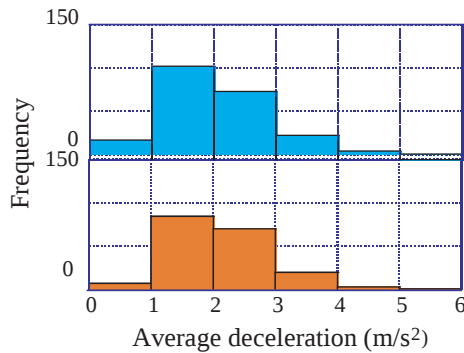
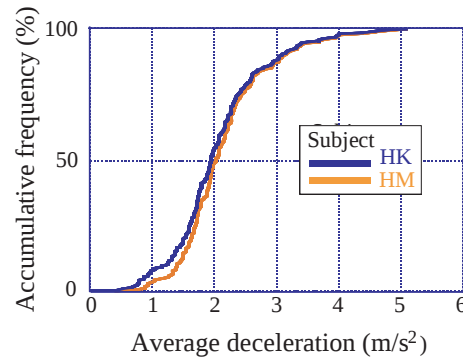


Fig. 11 Warning output frequency.



(a) Frequency distribution



(b) Accumulative frequency

Fig. 12 Average deceleration of the subject with different warning frequency.

subjects. According to the equation shown in Fig. 8, a warning is output when the distance to the vehicle in front is too small, but not when the distance is great enough to be safe. Therefore, we noted this distance at the instant that the brakes were first applied. The values for the Time To Collision (TTC) (given as: distance to the vehicle in front/vehicle velocity) at the start of braking are shown in **Fig. 13**. The subjects were the same as those shown in Fig. 12. Because the TTC for subject HK is greater than that for HM, we can say that HK applies the brakes earlier than HM. In other words, the difference in the warning output frequency depends on the TTC at the instant that the brakes are applied.

Figure 14 illustrates the subjective evaluation for subjects AN and HM. Ten warnings were issued for

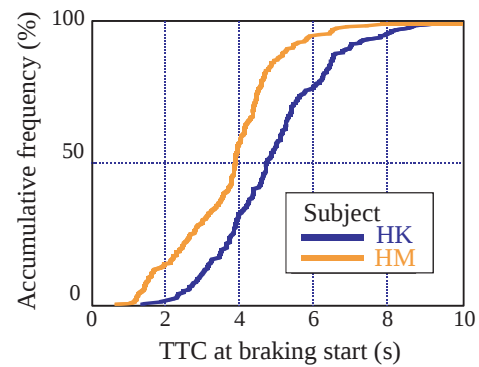


Fig. 13 TTC at the braking start of the subject with different warning frequency.

subject AN, as shown in Fig. 11, while 44 were issued for subject HM. Subject AN felt that about 70% of the warnings were necessary. Subject HM, however, felt that only about 5% of the warnings were necessary. Apart from subjects AN and HM, the trend in the subjectivity evaluation of the warnings was that those subjects for whom few warnings were issued felt the same way as AN, in that most of the warnings were necessary. Those subjects for whom many warnings were output, like HM, felt that the output frequency was too high.

Figure 15 shows the relationship between the subjective evaluation and average deceleration when a warning is output. For subjective evaluations 3 and 4, when the subject felt that the warnings were necessary, the average deceleration after the warning was larger than that for subjective evaluations 1 and 2, when the warnings were felt to be unnecessary. In

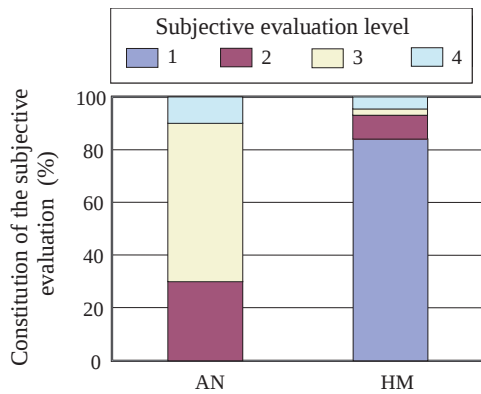


Fig. 14 Subjective evaluation.

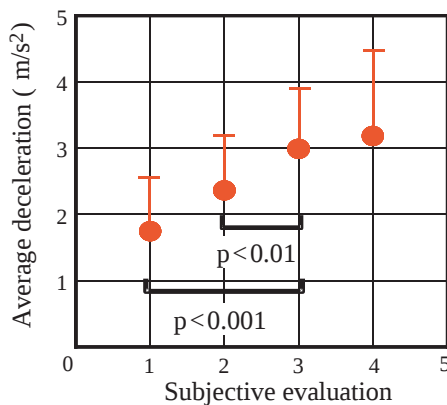


Fig. 15 The relationship between subjective evaluation and deceleration.

other words, we can know that the subject braked strongly when he or she felt that the warning was necessary.

Next, let's consider the braking when a warning is output continuously in an emergency situation. The number of warnings output during the experiment is shown in **Fig. 16**. For subjects EK and HM, many warnings were output. From this figure, we can see that the number of warnings output for both subjects fell by about 50% by continuing the experiment with PADSS. To investigate why the number of warnings decreased, we examined the intensity and the timing of the braking. There was no difference in the intensity of the braking between each journey of the experiment. **Figure 17** shows the TTC at the start of braking for journeys 3, 5 and 10 for subject HM. The TTC at the start of braking became larger as the experiment progressed. The large TTC implies an

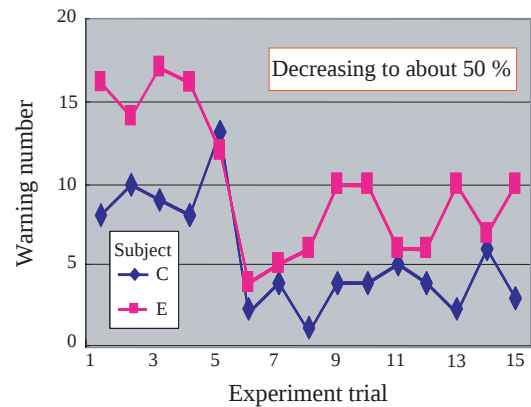


Fig. 16 Warning number during experiment continuing.

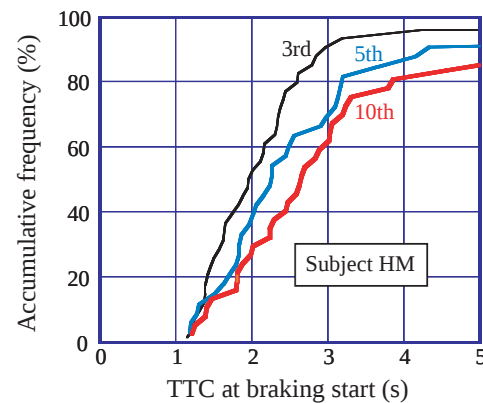


Fig. 17 TTC at the braking start during experiment continuing.

early braking start. Therefore, we can see that the driver learns to brake earlier by continuing the experiment with a warning being output in an emergency situation.

4.4 Warning reduction method using the TRDS analysis and development system

In this section, we describe two results obtained through the use of the TRDS analysis system, as shown in Fig. 10. First, we examined the warning algorithm with the goal of changing the parameter during braking. The warnings shown in Fig. 11 were output for about 75% of the subjects while braking. Most of the subjects regarded these warnings as being unnecessary. To reduce the number of unnecessary warnings output during braking, we improved the warning algorithm by changing the parameter from a 10% tile to a 2% tile during braking. The result for subject HM, who caused the greatest number of warnings to be output, is shown in Fig. 18. The left bar graph shows the number of warnings output, both when HM was braking and not braking. This subject observed 70% (= 31/44) of the warnings issued during braking. The center bar graph shows the simulation results obtained with the improved warning algorithm and the recorded data. (This data was that recorded in the first three experiments. The ratio of the warnings issued during braking fell from 70% to 43% (= 10/23) as a result of the improved warning algorithm. Based on this simulation, we can assume that number of warnings issued during braking will decrease. The right-hand bar graph in Fig. 18 shows

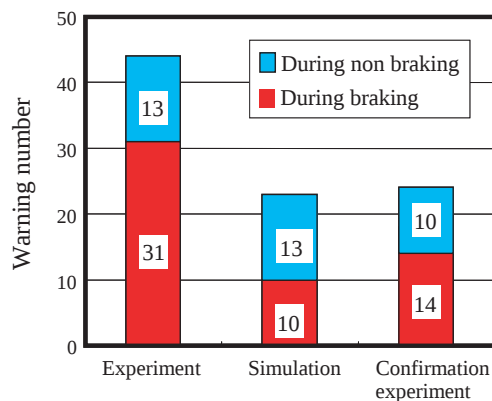


Fig. 18 Warning reduction by parameter change during braking.

the results obtained by using the improved warning algorithm with the modified parameter during braking. The number of warnings issued during braking falls in the same way as in the simulation. In addition, the total number of warnings falls from 44 to 24. This is reason enough to continue the PADSS experiment described above.

The second study with the TRDS analysis system is the use of the driver's gaze angle. We found that the subjects often felt that the issued warnings were unnecessary when his or her gaze was fixed on the vehicle in front. Based on the relationship between subject's measured gaze angle and the position of the vehicle in front, we can judge whether he or she is watching the vehicle in front. It would be very difficult for us to develop a warning algorithm that takes gaze angle into account and then repeat the experiment. The subject's gaze angle is measured by means of image processing using stereo-cameras mounted on the dashboard, as shown in Fig. 19. Using the TRDS analysis system, we can modify the warning algorithm and change the parameter if we know that the driver is watching the vehicle in front. The left-hand value (3) in Fig. 20 indicates the number of warnings output with the gaze angle considered, while the right-hand value (9) indicates the number of warnings output in a simulation using the same data but not taking the gaze angle into consideration.

The above two examples indicate that the TRDS analysis and development systems are able to confirm the experimental results and to effectively develop the warning algorithm.

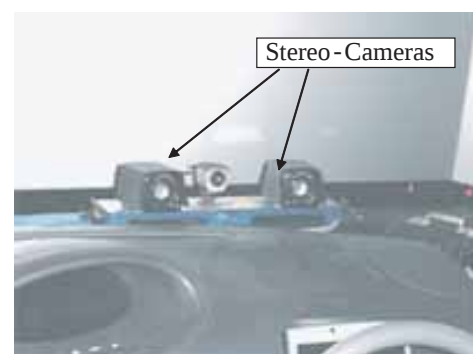


Fig. 19 Mounted stereo-cameras to measure the subject's gaze angle.

5. Conclusion

The TRDS driving simulator was developed to investigate a driving support system aimed at reducing road traffic accidents. TRDS is capable of analyzing a driver's behavior and supports system development based on accumulated data. The analyzed braking results, obtained with TRDS, differed depending on the driver and the place. Using the TRDS, a driving assistance PADSS, which adapts to personal braking habits, was developed. The output number of warnings was found to vary greatly depending on the subject. Those subjects for whom few warnings were output felt that the warnings were valuable, while those for whom many warnings were output often felt that the warnings were unnecessary.

Acknowledgements

This study is supported by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO), as a part of the project entitled "Behavior-Based Human Environment Creation Technology".

References

- 1) Jocoy, E. H. and Pierowicz, J. A. : "Treat Detection System for Intersection Collision Avoidance", SAE Tech. Pap. Ser., No.980851(1998)
- 2) Seiler, P., Song, B. and Hedrick, J. K. : "Development of a Collision Avoidance System", SAE Tech. Pap. Ser., No.980853(1998)
- 3) Nagiri, S., Amano, Y., Fukui, K., Doi, S. and Akamatsu, M. : "The Analysis of Driver Behavior for the Development of Driver Support System", 1st Human Centered Transp. Simulation Conf., (2001)
- 4) Sakaguchi, Y., Okuwa, M., Takiguchi, K. and Akamatsu, M. : "Measuring and Modeling of Driver for Detecting Unusual Behavior for Driving Assistance", Proc. of 18th Int. Tech. Conf. on the Enhanced Safety of Vehicles, (2003)
(Report received on Mar. 22, 2004)



Sueharu Nagiri

Year of birth : 1956
Division : Accident Prevention Lab.
Research fields : Driver behavior analysis,
Warning system, Driving simulator
Academic society : Soc. Autom. Eng.
Jpn., Jpn. Soc. Mech. Eng.



Yasushi Amano

Year of birth : 1957
Division : HV Electric Drive System Lab.
Research fields : Control system design,
Man-machine system,
Driver modeling
Academic degree : Dr. Eng.
Academic society : Soc. Autom. Eng.
Jpn., Jpn. Soc. Mech. Eng.,
Soc. Instrum. Control Eng.



Katsuhiko Fukui

Year of birth : 1955
Division : Vehicle Dynamics Control Lab.
Research fields : Driver behavior analysis,
Steering system analysis, Driving
simulator
Academic society: Soc. Autom. Eng. Jpn.



Shun'ichi Doi

Year of birth : 1947
Division : Dept. of Intell. Mech. Syst.,
Faculty of Eng., Kagawa Univ.
Research fields : Vehicle dynamics, Man-
machine systems active-safety
design/analysis
Academic degree : Dr. Eng.
Academic society : Soc. Autom. Eng.
Jpn., Jpn. Soc. Mech. Eng.,
Jpn., Soc. Instrum. Control Eng.
Awards : IR100 (1985), R&D100 (2000),
Award of Jpn. Soc. Instrum. Control
Eng. (1993)

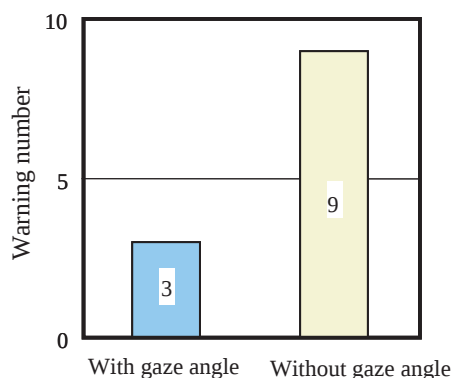


Fig. 20 Warning reduction by using gaze angle.