DRIVING SIMULATOR EXPERIMENT ON DRIVERS' BEHAVIOR AND EFFECTIVENESS OF DANGER WARNING AGAINST EMERGENCY BRAKING OF LEADING VEHICLE

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ABSTRACT

The purposes of this research are the followings: one is to investigate drivers' behavior and characteristics against the emergency braking of the leading vehicle by the JARI driving simulator. The other is to clarify the effectiveness of danger warning of the leading vehicle. For this analysis, the experiment using the JARI driving simulator was conducted. The virtual leading car on the simulator is controlled automatically and rapidly stops by the trigger command of a simulator operator. The subjects are 14 males in 20 to 29 ages.

From the experimental data, the difference of such variables to be analyzed as brake delay time, mean deceleration and minimum headway distance were compared between in case that the drivers cannot predict the emergency braking and in the case that they can predict it. As a result, those parameters in the unpredictable situation were larger than in the predictable situation.

In order to improve the driver's avoidance characteristics, effectiveness of danger warning against the emergency braking of the leading car was examined. The main effect and the interaction of the vehicle velocity, the warning time and the headway time on the variables to be analyzed were clarified by analysis of variance. The result of this test showed that the effect of the danger warning was recognized and the danger warning can make compensation for the increase of the brake delay time in the unpredictable situation.

INTRODUCTION

An advanced vehicle that installs some ITS systems warns a driver to avoid an obstacle detected automatically and/or starts automatic avoidance operations such as automatic braking and automatic steering. In a transitional period of the spread of the advanced vehicle, there is a traffic in which the advanced vehicle and an ordinary vehicle are intermixed. A driver getting on the ordinary car still perceives an obstacle manually to avoid it.

When the leading advanced vehicle quickly avoids an obstacle on the assumption that the ordinary car follows the leading vehicle, a driver getting on the ordinary car possibly behaves unsafely because of the leading vehicle movement contrary to his or her expectation. Besides, the ordinary car might disturb an advanced function of the advanced vehicle. For example, in case of the ordinary vehicle forces its way into the advanced vehicles, an automatic avoidance operation of the advanced vehicle may quite often function. Moreover, it is not found whether a driver who usually gets on the ordinary vehicle can adapt to the advanced vehicle or not, and vice versa. These are important problems in human factors area of ITS to promote the spread of its technologies.

The purposes of this research are the followings: one is to investigate drivers' behavior and characteristics against the emergency braking of the leading vehicle. The other is to clarify, the effectiveness of danger warning of the leading vehicle. Experiment using the JARI driving simulator is conducted.

HEADWAY DISTANCE IN ACTUAL VEHICLE

Test Method

Headway distance of each subject is measured by a laser radar installed in an actual vehicle on the JARI test course. The result is used for determining the initial headway distance defined next chapter.

The subjects (14 males in their twenties) drove the own vehicle to follow the leading vehicle an experimenter operated. The subjects were instructed to keep constant headway distance with consciousness of their ordinary driving. The speed of the leading vehicle was 60km/h. The subjective estimation of the headway distance was also recorded simultaneously.

Result

Comparison between headway distance measured by laser radar and by subjective estimation is shown in Figure 1. When the plotted points are on the 45 degrees line, the subjective estimation coincides with data measured by laser radar. According to Figure 1, most of the drivers estimate the headway distance to be less than the actual distance.

This result is utilized for checking initial conditions in simulator experiment against actual driving situations.

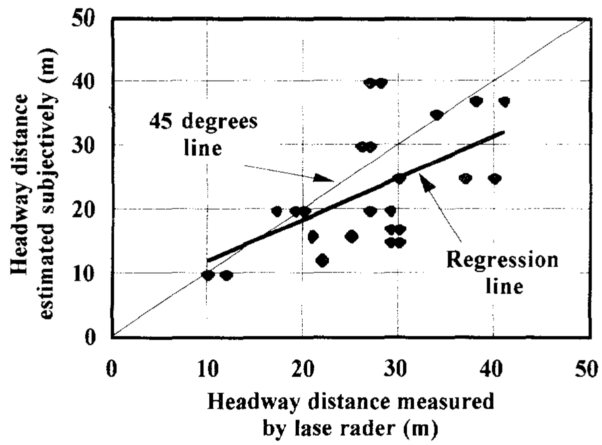

Figure 1. Headway distance of ordinary driving.

DRIVERS' BEHAVIOR AGAINST EMERGENCY BRAKING OF LEADING VEHICLE

Test Method using the Driving Simulator

Drivers' behavior against emergency braking of the leading vehicle was investigated in this test using the JARI driving simulator[1] to avoid real collision to the leading vehicle. As the computer graphics ofthe driving simulator creates the virtual leading vehicle, the subjects drives the car simulated by the driving simulator to follow the leading vehicle.

When the leading vehicle is about to stop, the subjects are allowed to operate steering and/or braking. The leading vehicle, however, turns left or right in accordance with a driver's steering action. Thus, unless the driver puts on the brake, the following vehicle that the driver operates necessarily collides with the leading vehicle. We did not inform the subjects of this matter.

Driving conditions in the driving simulator must be set for the actual situations in order to adjust experimental results to that by a real vehicle. In this test the headway distance measured by laser radar (chapter 2) was defined as the reference distance. We let the subjects keep the similar headway distance to the reference distance on the driving simulator.

The tasks and their scenarios are shown in Table 1.

Table 1. Tasks in Experiment

Task #	Velocity (km/h)	Deceleration (m/s^2)	Situation
1	60	0	Exercises
2	60	5	Unpredictable
3	60	5	Predictable
4	100	3	Predictable

The task #1 is exercise and impresses nothing ofthe rapid braking of the leading vehicle on the subjects, in order to perform the next task #2 successfully. The task #2 is a so-called surprise test in which the leading vehicle stops rapidly without prediction ofthe subjects. The headway distance before braking is set to the reference distance.

In the task #3 and #4 the subjects already knew the emergency braking ofthe leading vehicle. The emergency braking of the leading vehicle was put on at a random point of place every trial. The initial velocity and the deceleration of the leading vehicle were varied shown in Table 1. The subjects were allowed to try it twice every task. In the first trial the headway distance was set to the reference distance. In the second trial the headway distance was set to different distance according to the result of the first trial, i.e., ifthe collision occurred, the headway distance was longer than the reference distance; if it did not, the headway distance was shorter than the reference distance.

The leading vehicle is accelerated to the speed of 60 or 100km/h after the start, and keeps constant. At a certain place the step signal of deceleration is given to the leading vehicle (Figure 2). Simultaneously the stop lamps are turned on and the pitching angle ofthe leading vehicle is varied in proportion to the deceleration. If the own vehicle collides with the leading vehicle, the subjects can know the collision by blinking red light on the screen and the collision sound instead of the shock.

Definition of Variables to be Analyzed

The variables to be analyzed are defined as follows:

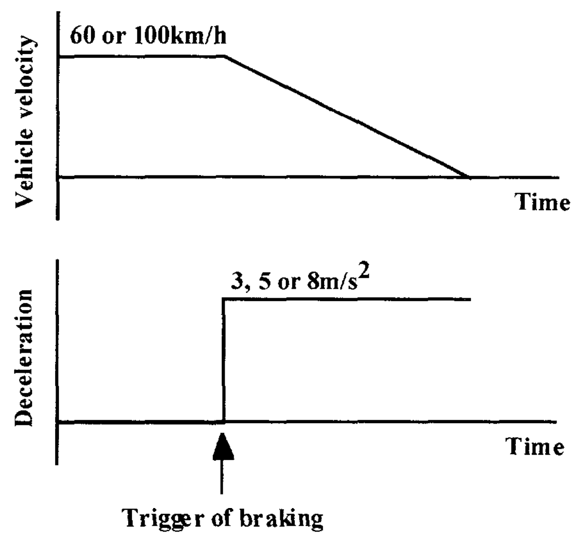

Figure 2. Pattern of deceleration of the leading vehicle.

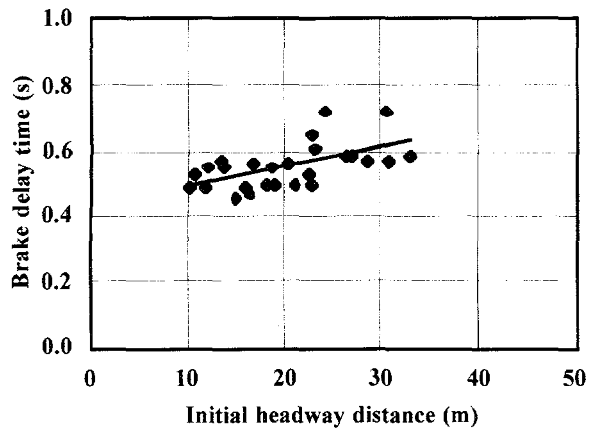

Figure 3. Relation between brake delay time and initial headway distance at 60km/h and $5m/s^2$.

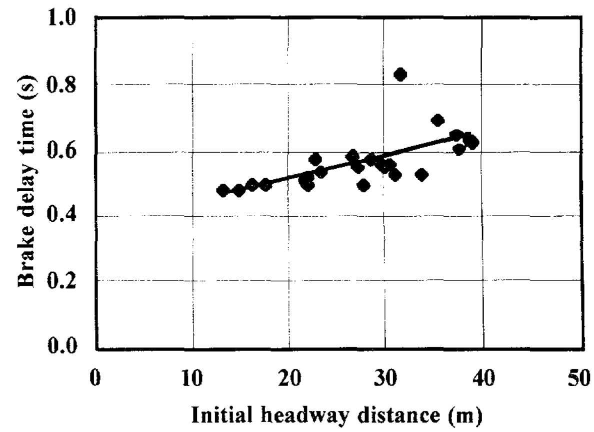

Figure 5. Relation between brake delay time and initial headway distance at 100km/h and $3m/s^2$.

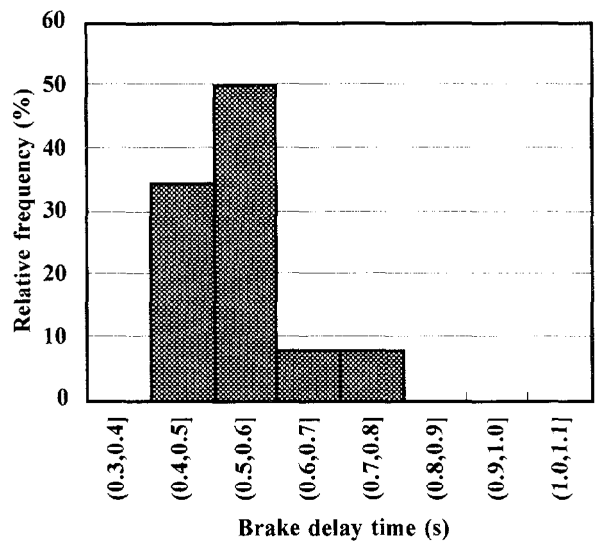

Figure 4. Relative frequency distribution of brake delay time.

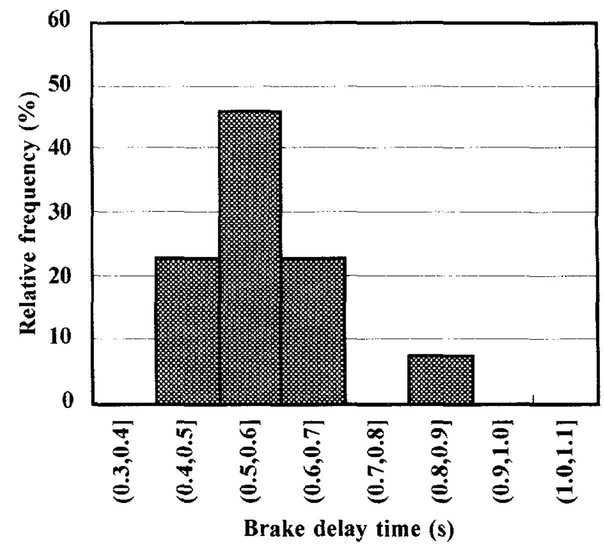

Figure 6. Relative frequency distribution of brake delay time at 100km/h & $3m/s^2$.

(1) *Initial headway distance*: it is a mean headway distance during 2seconds before the trigger of the emergency braking.
(2) *Minimum headway distance*: it is a headway distance when the own vehicle approaches the closest to the leading vehicle after the trigger of the emergency braking.
(3) *Brake delay time*: it is a time from the trigger of the emergency braking to the start of brake pedal operation of the subjects.
(4) *Mean deceleration*: it is an arithmetical mean of the own vehicle deceleration from the trigger of the emergency braking to the moment of the minimum headway distance.

Results in Predictable Situations

The results of task #3 and #4 are shown here.

Brake delay time - Figure 3 shows the relation between brake delay time and initial headway distance at the velocity of 60km/h and the deceleration of $5m/s^2$ (task #3). The brake delay time slightly increases with the initial headway distance. Figure 4 is relative frequency distribution of the brake delay time. The ratio of (0.5s, 0.6s] is about 50%, and the ratio of (0.4s, 0.6s] occupies approximately 85%, where "(" means "more than" and "]" means "less than or equal to".

Figure 5 shows the relation between brake delay time and initial headway distance at the velocity of 100km/h and the deceleration of $3m/s^2$ (task #4). The brake delay time

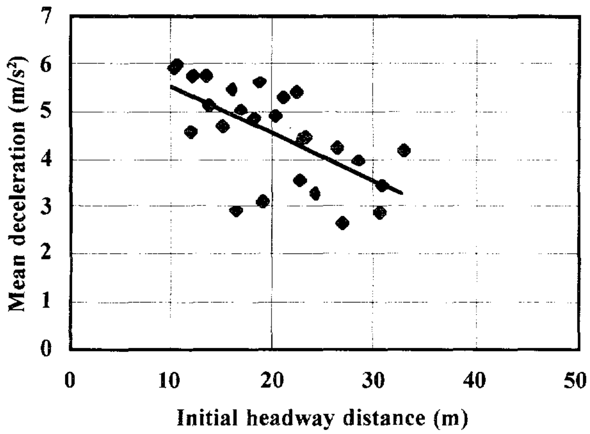

Figure 7. Relation between mean deceleration and initial headway distance at 60km/h and $5m/s^2$.

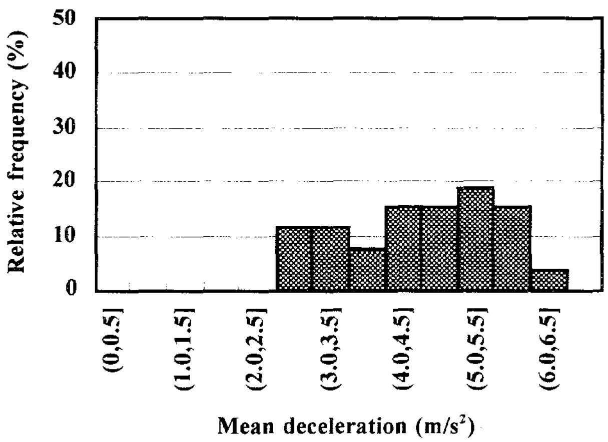

Figure 8. Relative frequency distribution of mean deceleration at 60km/h and $5m/s^2$.

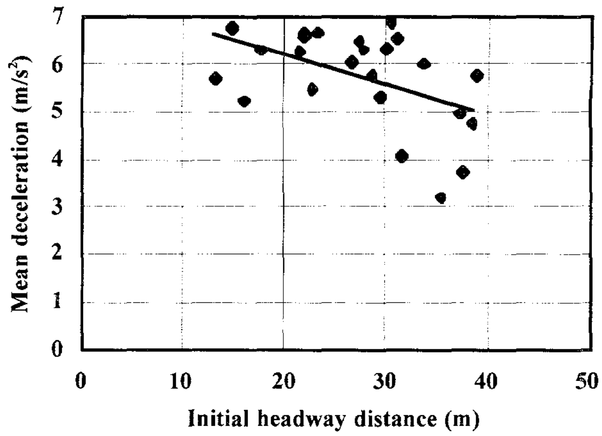

Figure 9. Relation between mean deceleration and initial headway distance at 100km/h and $3m/s^2$.

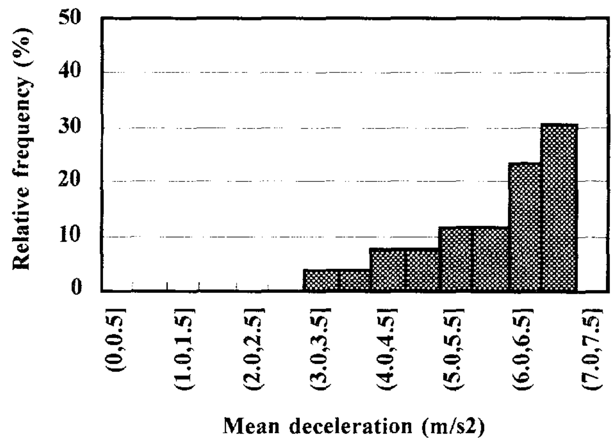

Figure 10. Relative frequency distribution of mean deceleration at 100km/h and $3m/s^2$.

becomes a little smaller than the previous result. Figure 6 is also relative frequency distribution of the brake delay time. The brake delay time at peak ratio is the same as the previous result.

Mean deceleration - Figure 7 shows the relation between mean deceleration and initial headway distance at the velocity of 60 km/h and the deceleration of $5m/s^2$ (task #3). The mean deceleration decreases with the increase of the initial headway distance. Figure 8 is relative frequency distribution of the mean deceleration. Although the peak is at ($5.0m/s^2$, $5.5m/s^2$], it is widely distributed from $2.5m/s^2$ to $6.5m/s^2$.

Figure 9 shows the similar relation at the velocity of 100km/h and the deceleration of $3m/s^2$ (task #4). The mean deceleration is larger than that in the result of 60km/h. This tendency is represented by the distribution in Figure 10. The peak is at ($6.5m/s^2$, $7.0m/s^2$], and its ratio occupies about 30%.

Minimum headway distance - Figure 11 shows the relation between minimum headway distance and initial headway distance at the velocity of 60km/h and the deceleration of $5m/s^2$ (task #3), where the minimum headway distance less than or equal to 0 m means the rear-end collision. In figure 11 the regression curve of the minimum headway distance decreases with reduction of the initial headway distance. This curve reveals that the rear-end collision occurs less than about 10m of the initial headway distance (this boundary of initial headway distance is defined as critical headway distance).

Figure 12 shows the similar result at the velocity of 100km/h and the deceleration of 3m/s2 (task #4). The critical headway distance is about 17m; I.e., the collision occurs less than about 17m of initial headway distance.

Results in Unpredictable Situation

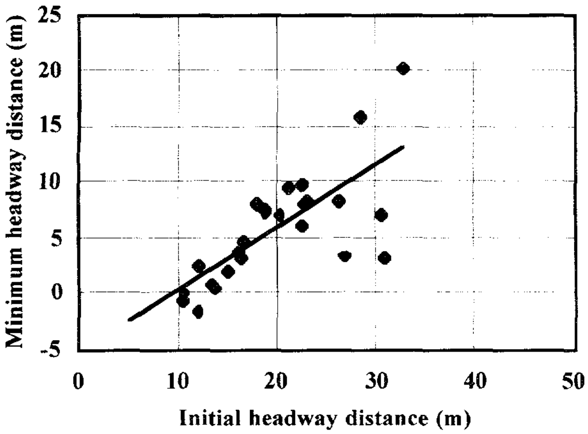

Figure 11. Relation between minimum headway distance and initial headway distance at 60km/h and $5m/s^2$.

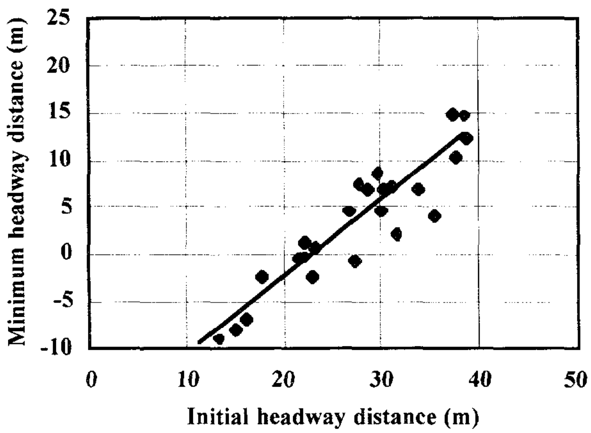

Figure 12. Relation between minimum headway distance and initial headway distance at 100km/h and $3m/s^2$.

The results of the task #2 in which the emergency braking put on the leading vehicle without prediction ofthe subjects are shown in this section. The experimental conditions are the same as the task #3 except the unpredictable situation.

Brake delay time - Figure 13 shows that the relation between brake delay time and the initial headway time. The increase tendency in the relation is similar to the predictable situation, task #3. The relative frequency distribution is shown in Figure 14. As the ratio of (0.7s, 0.8s] is about 55%, the brake delay time is about 0.2s larger than the predictable situation.

Mean deceleration - Figure 15 shows that the relation between the mean deceleration and the initial headway distance. The mean deceleration decreases with the increase of the initial headway distance as well as that ofthe predictable situation. The relative frequency distribution is, however, different from that in the predictable situation because Figure

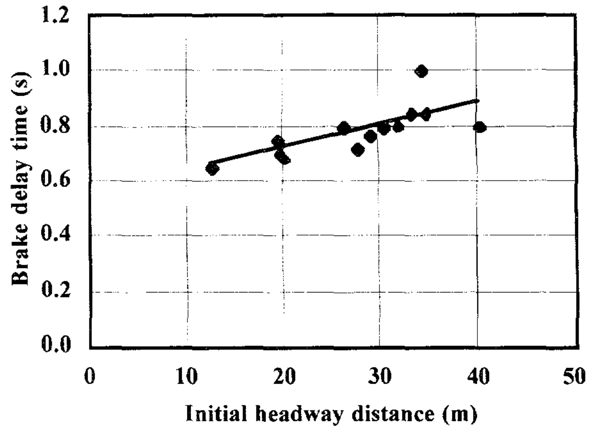

Figure 13. Relation between brake delay time and initial headway distance at 60km/h and $5m/s^2$ in unpredictable situation.

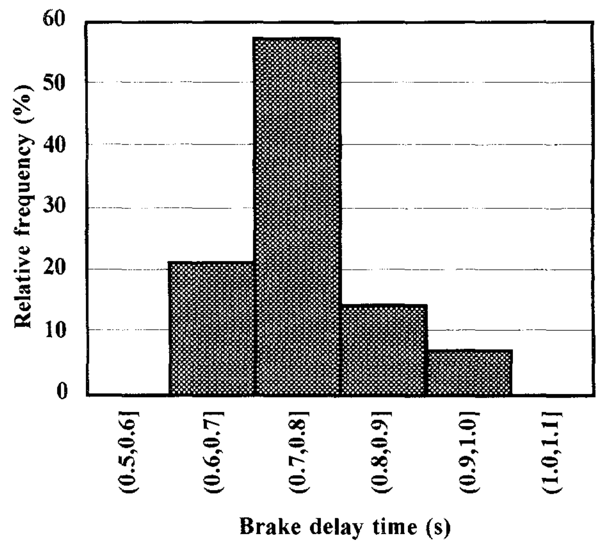

Figure 14. Relative frequency distribution of brake delaty time in unpredictable situation.

16 reveals that the peak is at ($1.5m/s^2$, $2.0m/s^2$] and the distribution range is narrower than that in the task #3.

Minimum headway distance - Figure 17 shows that the relation between minimum headway distance and the initial headway distance. The regressive curve in Figure 17 reveals that the critical headway distance is about 15m. This value is larger than the predictable situation in spite of the fact that the experimental conditions are the same except predictable or unpredictable. In addition to this, although the minimum headway distances at the initial headway distance of20m and 30m are about 6m and 11m respectively in the predictable situation, task #3, those are about 3m and 8m respectively in the unpredictable situation, task #2.

Comparison between the predictable situation and the unpredictable situation - Thus, the following results

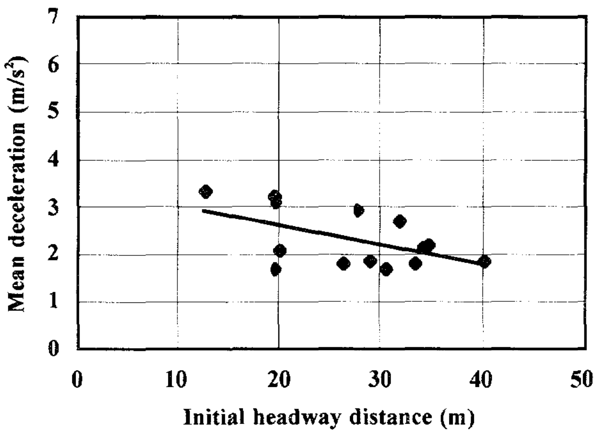

Figure 15. Relation between mean deceleration and initial headway distance at 60km/h and 5m/s^2 in unpredictable situation.

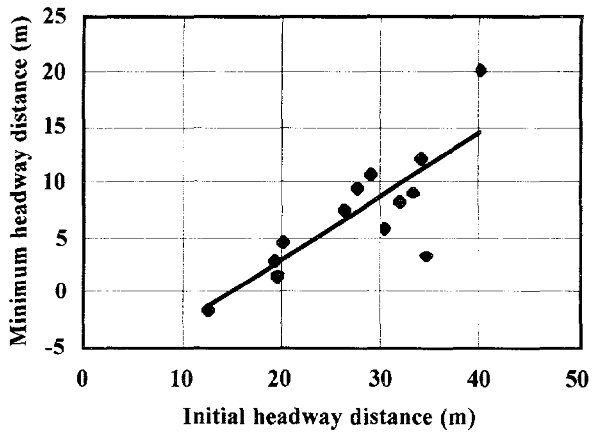

Figure 17. Relation between minimum headway distance and initial headway distance at 60km/h and 5m/s^2 in unpredictable situation.

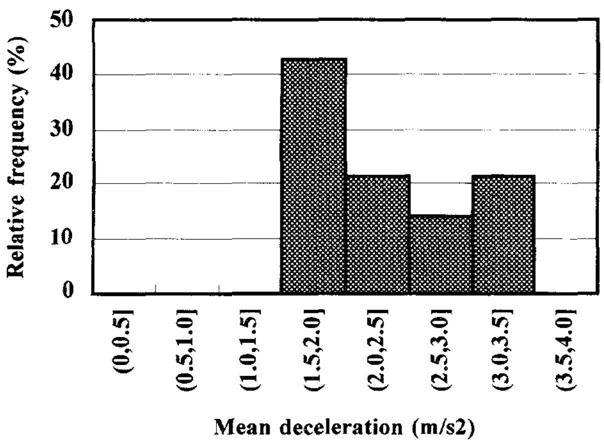

Figure 16. Relative frequency distribution of mean deceleration in unpredictable situation.

are obtained: in the unpredictable situation in comparison with the predictable situation,

(1) the brake delay time is about 0.2s larger,

(2) the mean deceleration is about 4m/s^2 smaller,

(3) the critical headway distance is about 5m larger.

Therefore, possibility of the collision becomes high if a leading vehicle rapidly decelerates when an own car follows with short headway distance without anticipation of a driver. One of the improvements is an assist from the leading vehicle with danger warning. Next chapter the effectiveness of the danger warning is examined.

EFFECTIVENESS OF DANGER WARNING AGAINST EMERGENCY BRAKING

Method of Danger Warning

In order to clarify the effectiveness of the danger warning, the following experiment was conducted. When the subject starts the own vehicle, the leading vehicle starts at the same time. The leading vehicle automatically keeps the headway time (headway distance / vehicle velocity) to be 0.7s or 1.0s. The subject controls the speed to be 60 or 100km/h, and the leading vehicle runs at the same speed. The deceleration of the leading vehicle after the braking trigger is the step of 8m/s^2. The trigger point of place was set randomly every trial.

The danger warning was generated using the stop lamps of the leading vehicle. They were lighted up 0.3s before the trigger of the braking. This time is defined as the warning time. The subjects can know the emergency braking of the leading vehicle before the trigger.

The tasks are from task A to J shown in Table 2. The order of the tasks of each subject was changed to eliminate the order effect. Analysis of variance is performed using the data of this experiment.

Table 2.
Tasks in Experiment with Danger Warning

Task	Velocity (km/h)	Deceleration (m/s^2)	Headway time (s)	Warning time (s)
A	60	8	0.7	0.0
B	60	8	0.7	0.3
C	60	8	1.0	0.0
D	60	8	1.0	0.3
E	100	8	0.7	0.0
F	100	8	0.7	0.3
G	100	8	1.0	0.0
H	100	8	1.0	0.3
I	100	8	0.5	0.0
J	100	8	0.5	0.3

Table 3.
Result of Analysis of Variance in Brake Delay Time

	SS	df	MS	F
A: Velocity	0.034	1	0.034	1.99
B: Warning time	1.922	1	1.922	112.89 **
C: Headway time	0.015	1	0.015	0.90
A x B	0.00026	1	0.000	0.02
B x C	0.0056	1	0.006	0.33
A x B	0.0261	1	0.026	1.53
A x B x C	0.0017	1	0.002	0.10
e	1.770	104	0.017	

Significant level: **<0.01 *<0.05

Table 4.
Result of Analysis of Variance in Mean Deceleration

	SS	df	MS	F
A: Velocity	15.276	1	15.276	94.358 **
B: Warning time	0.694	1	0.694	4.285 *
C: Headway time	0.305	1	0.305	1.882
A x B	0.027	1	0.027	0.165
B x C	0.272	1	0.272	1.681
A x C	0.352	1	0.352	2.175
A x B x C	0.001	1	0.001	0.005
e	16.837	104	0.162	

Significant level: **<0.01 *<0.05

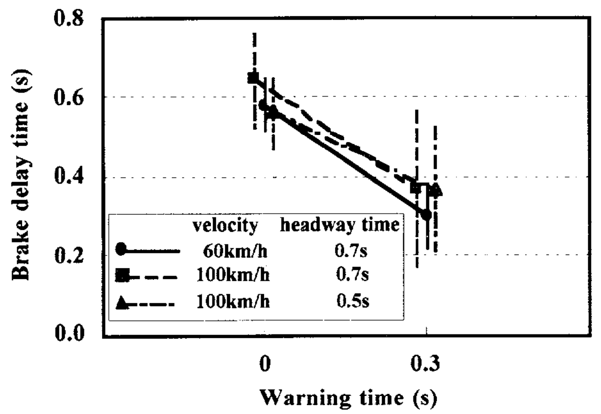

Figure 18. Relation between brake delay time and warning time (average and standart deviation).

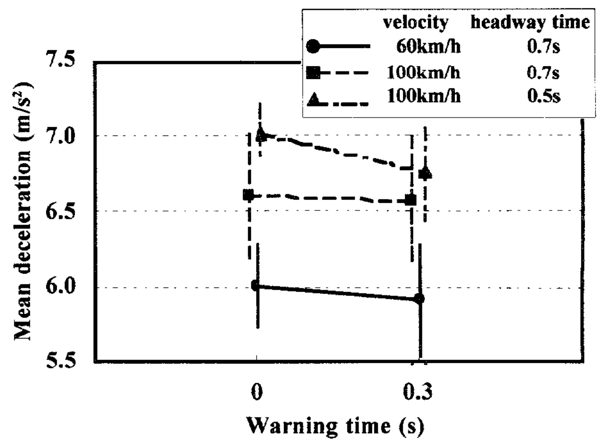

Figure 19. Relation between mean deceleration and warning time (avelage and standart deviation).

Effectiveness of Danger Warning

Brake Delay Time - The result of analysis of variance is shown in Table 3. Only the main effect of the warning time has significant difference.

Figure 18 shows the relation between the brake delay time and the warning time with the vehicle velocity and the headway time as parameters. The brake delay time becomes short when the warning time is 0.3S (the stop lamps light up 0.3s before the trigger of the braking). The decrease of the brake delay time is about 0.25s. It is almost equal to both the warning time and the difference between the brake delay time in predictable situation and in the unpredictable situation mentioned in the previous chapter. Thus, at least about 0.3s is required of the warning time.

Mean Deceleration - The result of analysis of variance is shown in Table 4. The main effect of the vehicle velocity and the warning time have significant difference. The former and the latter significant level are 1% and 5% respectively. The interaction is not detected as well as the result of the brake delay time.

Figure 19 shows the relation between the mean deceleration and the warning time with the vehicle velocity and the headway time as parameters. Although the significant difference of the warning time is detected in Table 4, the effect of the warning time is recognized only at the vehicle velocity of 100km/h and the headway time of 0.5s in Figure 19. The warning time has almost no effect on the mean deceleration.

Minimum Headway Distance - The result of analysis of variance is shown in Table 5. The main effect of all the variables: the vehicle velocity, the warning time and the headway time have significant difference. And then, the interaction between the vehicle velocity and the headway distance is detected with 5% of the significant level.

Figure 20 shows the relation between the minimum headway distance and the warning time with the vehicle velocity and the headway time as parameters. When the warning time is 0.3s, the minimum headway distance becomes larger. The collision occurs only at the vehicle velocity of 100km/h and the headway time of 0.5s in this warning time.

The increase in the minimum headway distance is

Table 5 Result of analysis of variance in minimum headway distance

	SS	df	MS	F
A: Velocity	407.12	1	407.12	15.842 **
B: Warning time	957.68	1	957.68	37.266 **
C: Headway time	969.64	1	969.64	37.732 **
A x B	83.52	1	83.52	3.250
B x C	16.59	1	16.59	0.646
A x C	169.78	1	169.78	6.607 *
A x B x C	2.07	1	2.07	0.081
e	2672.63	104	25.69	

Significant level: **<0.01 *<0.05

shown in Table 6. The increase at the headway distance of 0.7s is equal to the distance covered during the warning time of 0.3s. The increase is, however, less than "the warning time multiplied by the vehicle velocity" at the vehicle velocity of 100km/h and the headway time of 0.5s. Thus, in case the headway distance is relatively large, the minimum headway distance can be expanded to the distance added "the warning time multiplied by the vehicle velocity" by the danger warning. And then, the shorter the headway time, the harder the increase of the minimum headway distance.

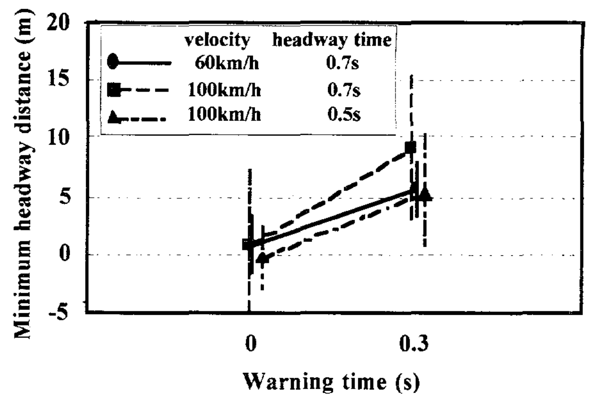

Figure 20. Relation between minimum headway distance and warning time (average and standard deviation).

Tavle 6.
Increase of Minimum Headway Distance by Danger Warning

Conditions		Minimum headway distance (m)			
Velocity (km/h)	Headway time (s)	at warning time 0.0s	at warning time 0.3s	Increase of minimum headway distance (m)	Velocity multiplied by warning time (m)
60	0.7	1.02	5.64	4.62	5.00
100	0.7	0.37	8.99	8.62	8.33
100	0.5	-0.72	4.94	5.67	8.33

The relation between the headway time and the minimum headway distance with the vehicle velocity as a parameter is shown in Figure 21, because there is the interaction between vehicle velocity and the headway time. Although the average at 60km/h is a little larger than that at 100km/h at the headway time of 0.7s, the average at 100km/h is much larger than that at 60km/h at the headway time of 1.0s. There is much difference of the minimum headway distance to variation of the vehicle velocity in case of large headway time.

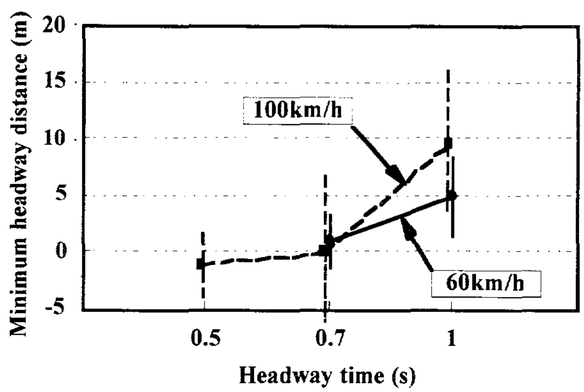

Figure 21. Interaction between vehicle velocity and headeay time (average and standard deviation)

CONCLUSIONS

In this research drivers' behavior and characteristics against the emergency braking of the leading vehicle was investigated using the JARI driving simulator. Besides, the effectiveness of danger warning of the leading vehicle was clarified. The following results were obtained:

(1) In the unpredictable situation the brake delay time and the critical headway distance are about 0.2s and 5m larger respectively, and the mean deceleration is $4m/s^2$ smaller than in the predictable situation.

(2) The main effect having the significant difference are (a) the warning time on the brake delay time, (b) the vehicle velocity and the warning time on the mean deceleration, and (c) the vehicle velocity, the warning time and the headway time on the minimum headway distance. There is also the interaction between the vehicle velocity and the headway time on the minimum headway distance.

(3) The effect of the danger warning is recognized. In case the headway distance is relatively large, the minimum headway distance can be expanded to the distance added "the warning time multiplied by the vehicle velocity" by the danger warning. Thus, the danger warning can make compensation for the increase of the brake delay time in the unpredictable situation. However, at least about 0.3s is required of the warning time.

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