Preliminary Study of Behavioral and Safety Effects of Driver Dependence on a Warning System in a Driving Simulator

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***Abstract*—Warning systems are being developed to improve traffic safety using visual, auditory, and/or tactile displays by informing drivers of the existence of a threat in the roadway. Behavioral and safety effects of driver dependence on such a warning system, especially when the warning system is unreliable, were investigated in a driving-simulator study. Warning-system accuracy was defined in terms of miss rate (MR) and positive predictive value (PPV) (PPV is the fraction of warnings that were correct detections). First, driver behavior and performance were measured across four warning-system accuracy conditions. Second, the authors estimated the probability of collision in each accuracy condition to measure the overall system effectiveness in terms of safety benefit. Combining these results, a method was proposed to evaluate the degree of driver dependence on a warning system and its effect on safety. One major result of the experiment was that the mean driving speed decreased as the missed detection rate increased, demonstrating a decrease in driver's reliance on warnings when the system was less effective in detecting threats. Second, both the acceleration-pedal and brake-pedal reaction times increased as the PPV of the warning system decreased, demonstrating a decrease in driver compliance with warnings when the system became more prone to false alarms. A key implication of the work is that performance is not necessarily directly correlated to warning-system quality or trends in subjective ratings, highlighting the importance of objective evaluation. Practical applications of the work include design and analysis of in-vehicle warning systems.**

***Index Terms*—Alarm systems, automation, driver information systems, human factors, safety.**

I. Introduction

VARIOUS driver support system technologies, such as adaptive-cruise-control systems or in-vehicle collision warning systems, are being developed to improve traffic safety. A solid understanding of the effects these systems may have on driver behavior and safety is important to predict the effectiveness of the systems and also to ensure that unintended risks are not introduced [1]–[7]. One such technology of current particular interest is a warning system that informs the driver of the existence of a threat, such as an obstacle or a pedestrian in or near the roadway before the obstacle becomes visible to the driver. Any of these systems can be based on sensors, decision algorithms, and display of information to the driver. In the real world, these sensors and decision algorithms only guarantee a certain level of accuracy and, therefore, actual warning systems occasionally generate false alarms (FA) or missed obstacles.

A warning system can be considered a form of automation including mechanical or electrical replacement of some subset of human monitoring and decision making, with a requisite human-factor interaction schema [8], [9]. The effectiveness of a warning system is strongly related to the operators' trust—this is a central research problem on the operators' use of automation in general [10], [11]. It has been shown that operators are likely to change their baseline behavior and their responses to warnings due to adaptation and bias after observing the automation at work over some period of time [12], [13]. When FAs are common, operators may learn to ignore warnings or delay response, defeating the whole purpose of the warning system [14]–[17]. On the other hand, operators may learn to rely too strongly on a warning system and may miss additional information, a phenomenon akin to misuse of automation or automation bias [18].

It has been proposed that trust in warning systems consists of two distinct components: compliance and reliance [19]. Compliance accounts for an operator responding appropriately when there is actually a problem identified by a warning. Reliance accounts for the operator assuming that the system is in a safe state when no warning is given. It has been hypothesized that a reduction in driving speed following a warning indicates a driver's compliance with the system, and a higher mean driving speed when no warning is given reflects the driver's reliance on the system [20]. The experiment described in this paper was intended to examine these hypothesized relationships.

Our research focused on a warning system that informs the driver of the existence of a pedestrian ahead of the vehicle before that pedestrian becomes visible to the driver at nighttime. This is an application that is currently being pursued in the automotive industry [21]–[24]. However, there has been a little research on the human-factor issues behind limited-information quality in this type of warning system. The objective of this research was to investigate behavioral and safety effects of driver dependence on the warning system in a driving-simulator study, and to obtain objective measurements of driver dependence and determine the implications for driver behavior and safety.

There are two kinds of dependence on a warning system as described above: reliance and compliance. It is hypothesized that the degree of compliance or reliance will depend on the

Manuscript received August 31, 2004; revised April 7, 2005. The work of J. Kuchar was performed while the author was with MIT, Cambridge. This paper was recommended by Associate Editor N. Hari Narayanan.

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Digital Object Identifier 10.1109/TSMCA.2006.871646

Fig. 1. Experimental setup. A warning to indicate the existence of a pedestrian was provided visually to the driver using a simulated head-up display.

perceived accuracy of the warning system. That is, the smaller the miss rate (MR) is, the more the driver can rely on the warning system while no warning is issued. The larger the positive predictive value (PPV) is (PPV, the fraction of warnings that were correct detections), the more likely it is that the driver will comply with the warning. By observing variations in the drivers' behavior as the warning-system accuracy is varied, we can then measure the behavioral and safety effects of driver dependence on a warning system in terms of driving speed, acceleration-pedal reaction time, brake-pedal reaction time, and the number of collisions, and thereby measure the human factors' impacts of system errors, such as misses and FAs.

Based on this hypothesis, a human-in-the-loop experiment was conducted using a driving simulator. This first involved measuring the behavioral impact of warning-system quality on the drivers' performance. Second, we estimated the probability of collision for each test condition from the observed average and standard deviation of vehicle speed as well as the actual collision rate and used it to measure the overall system effectiveness in terms of safety benefit. Combining these results, a methodology for evaluating the degree of driver dependence on a warning system and its effect on safety is proposed.

II. METHOD

A. Participants and Apparatus

Nine males and one female participated in the experiment. The subjects ranged from 29 to 41 years of age with a mean of 32. All were licensed drivers and had five or more years of driving experience with a mean of ten years. The subjects were instructed that this study was designed to evaluate the potential benefits of a warning system during the nighttime driving tasks. The subjects were not told of the goal of this study nor the underlying hypotheses. All participants were paid a U.S. $20 honorarium. No bonuses or penalties were levied on the subjects for their performance in the driving simulation.

A fixed-base driving simulator composed of STISIM software from Systems Technology, Inc. and an actual 2000 Volkswagen Beetle chassis and body were used for the experiment. Fig. 1 shows a photograph of the experimental setup. The driving scene was displayed on a screen positioned 2.7 m in front of the driver using an liquid crystal display (LCD) projector. The field of view of the scene was 50° horizontal by 39° vertical. Sound was projected through a speaker to represent engine noise, tires screeching, and a crash sound when the vehicle collided with either another vehicle, a pedestrian, or the edge of the roadway. The subjects drove the vehicle using a steering wheel, acceleration pedal, and brake pedal in standard locations. The driving speed was indicated with a dashboard speedometer. A warning to indicate the existence of a pedestrian ahead was provided visually to the driver using a simulated head-up display, with a yellow rectangle superimposed at the bottom of the out-the-window view, at an angular size of 6° horizontal by 1° vertical. The only obstacles in this experiment were pedestrians; an actual warning system would need an additional testing to determine its ability to distinguish various types of obstacles.

		Truth	
		Pedestrian	No-Pedestrian
Detection	Pedestrian	TP (True Positive)	FA (False Alarm)
	No-Pedestrian	MS (Miss)	TN (True Negative)

Miss Rate: MR = MS/(TP+MS)
False Alarm Rate: FAR = FA/(FA+TN)
Positive Predictive Value: PPV = TP/(TP+FA)

Fig. 2. Definitions of MR and PPV. MR is defined as the ratio of the number of pedestrians missed by the warning system to the total number of pedestrians in a scenario; PPV is defined as the ratio of the number of TPs (issued when a pedestrian was present) to the total number of warnings in a scenario.

B. Design and Procedure

The independent variable in the study was the accuracy of the warning defined in terms of its MR and PPV. According to the signal detection theory [25], as explained in Fig. 2, MR is defined as the ratio of the number of pedestrians missed by the warning system to the total number of pedestrians in a scenario; PPV is defined as the ratio of the number of true positive (TP) warnings, issued when a pedestrian was present, to the total number of warnings in a scenario. As shown in Table I, four conditions, including a condition in which no warning system was present, were experienced by each subject, encoded as pairs (MR, PPV). The four conditions were $(\mathrm{MR}, \mathrm{PPV}) = (1.0, -($PPV was not applicable because there were no warnings$))$, (0.5, 1.0), (0.25, 1.0), and (0.25, 0.5).

Table II shows the experiment design. Each test scenario was a 10-km long suburban road at nighttime split into two equal "blocks" of 5 km. The first block in each scenario was used to provide the subject with some experience in a given warning-system condition; the second block was used for data collection. All of the blocks were identical except for the order and timing of warning and pedestrian events. Each subject ran through four such scenarios, each under a different controlled condition, as shown in Table I. Three conditions, B, C, and D, in which warnings were presented, were counterbalanced as a block. A total of 12 ordered conditions were generated, six when condition A

TABLE I
EXPERIMENTAL CONDITIONS

Condition ID	Block	Length (km)	Number of Events					Miss Rate (*MR*)	Positive Predictive Value (*PPV*)
			Pedestrian				False Alarm (No-Pedestrian)		
			Crossing		Sidewalk				
			True Positive	Miss	True Positive	Miss			
A	1	5	0	4	0	4	0	1.0	– *
	2	5	0	4	0	4	0		
B	1	5	2	2	2	2	0	0.5	1.0
	2	5	2	2	2	2	0		
C	1	5	3	1	3	1	0	0.25	1.0
	2	5	3	1	3	1	0		
D	1	5	3	1	3	1	6	0.25	0.5
	2	5	3	1	3	1	6		

* Not applicable because there was no warning

TABLE II
EXPERIMENT DESIGN

Condition ID	*MR*	*PPV*
A	1.0	–
B	0.5	1.0
C	0.25	1.0
D	0.25	0.5

Subject #	Order of the Conditions			
	1	2	3	4
02	A	B	D	C
08	A	C	B	D
04	A	C	D	B
10	A	D	B	C
06	A	D	C	B
09	B	C	D	A
03	B	D	C	A
01	C	B	D	A
05	D	B	C	A
07	D	C	B	A

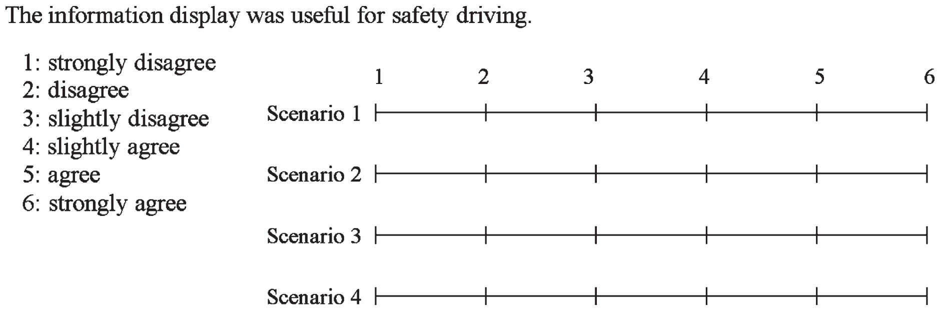
was used before the B, C, and D blocks, and six when condition A was used after the B, C, and D blocks. Due to a limitation in recruiting subjects, ten of the 12 combinations (five of the first six and five of the last six) were randomly selected, and ten subjects were randomly assigned. The order of the scenarios that each subject experienced was the same, whereas the order of the conditions (A–D) was different for each subject.

During each 10-km drive, a total of 16 pedestrians appeared at the roadside. Eight of the 16 pedestrians crossed the road in front of the vehicle from either the left or right sidewalk, and eight other pedestrians walked on either sidewalk staying clear of the roadway. Each pedestrian began to walk across the road or along the sidewalk at a speed of 0.55 m/s when the time to collision (TTC) between the vehicle and the pedestrian was 5 s. Note that this gait is slower than the average walking speed of adults at free cadence, approximately 1.3 m/s [26], and that the pedestrian may have been stationary for some time before moving, depending on the driver's speed. The order and timing of warning and pedestrian events were randomized.

The scenarios were carefully designed so that the driver would collide with a crossing pedestrian unless the vehicle was decelerated. The visible range was set to 75 m and the warning was presented when the car was 110 m away from each pedestrian. Note that in this study, a TP was one where there was a pedestrian present, regardless of whether that pedestrian stepped into the roadway. FAs occurred when a warning was given but no pedestrian appeared at all.

Each subject ran four test scenarios, one at each of the four levels of warning accuracy as seen in Table I. The subjects were told that they would experience a different system, or accuracy of warnings, on each run. The instructions to the subjects included: 1) drive the car at a comfortable speed without colliding with pedestrians; 2) a warning on the existence of a pedestrian ahead may be given, but it may not be perfectly accurate; and 3) the length of each scenario is 10 km. Before starting the test runs, the participants ran a practice scenario that was similar to an actual test scenario without the warning system to become familiar with the simulator configuration and driving environment. Then, the participants ran another practice scenario that was similar to the actual test scenarios with the warning system except that the warning system operated with 100% accuracy, with neither misses nor FAs.

The dependent variables in the study were driving speed, defined as the speed at the moment the car was 110 m away from a pedestrian, acceleration-pedal reaction time $\mathrm{RT_A}$, and brake-pedal reaction time $\mathrm{RT_B}$. The reaction times were measured relative to the moment the car was 75 m from the pedestrian, that is, from the moment the pedestrian became visible to the driver. In addition, the subjects were asked to rate the system in terms of safety, comfort, and annoyance, and also to estimate the MR and FA ratio $(1 - \mathrm{PPV})$ for each test run. Fig. 3 shows an example of how the subjects were asked to rate the system in the questionnaire. As described earlier, the data obtained in



The information display was useful for safety driving.

1: strongly disagree
2: disagree
3: slightly disagree
4: slightly agree
5: agree
6: strongly agree

	1	2	3	4	5	6
Scenario 1						
Scenario 2						
Scenario 3						
Scenario 4						

Fig. 3. Example section of the subjective questionnaire.

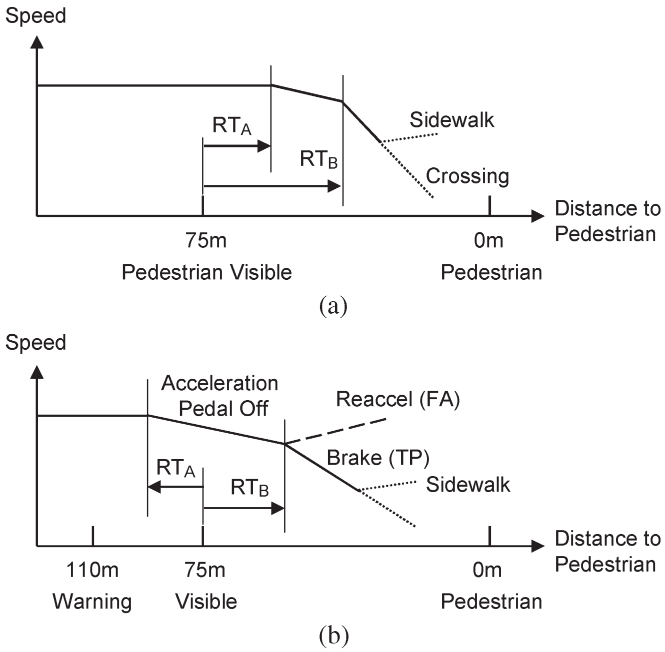


Fig. 4. Typical driving strategy when (a) no warning system was used or when the pedestrian was missed by the system and (b) when TP or FA was given.

the latter half (second block) of each test run were used for analysis so that the subjects could become accustomed in the first block to the accuracy of the warning system used in that test condition. The expected length of time for the experimental procedure was 2 h including the instructions, practice, and subjective ratings.

III. RESULTS AND DISCUSSION

A. *Typical Driving Strategy*

Fig. 4 shows a notional typical driving strategy that the drivers adopted to avoid a collision with a pedestrian. When no warning system was used or when the pedestrian was missed by the warning system [Fig. 4(a)], the drivers generally released the acceleration pedal and pushed the brake pedal shortly after the pedestrian became visible to the drivers at 75 m. On the other hand, when a warning was given [Fig. 4(b)], the drivers generally released the acceleration pedal, in response to the warning, before the pedestrian was visible. The drivers applied the brake after the pedestrian became visible if the warning was a true positive. Otherwise (when the warning was an FA), the drivers accelerated back to their normal driving speed, as shown with a broken line.

B. *Effects on Driving Speed and RT*

The effects of warning accuracy on the driving speed, acceleration-pedal reaction time $\mathrm{RT_A}$, and brake-pedal reaction time $\mathrm{RT_B}$, for the second block in each scenario, are shown in Fig. 5(a)–(c), respectively. Note that the error bars in the figure represent standard deviation. Note also that, because the experiment was a within-subject design, overlapping error bars do not necessarily indicate that the differences between averages were not significant.

First, consider the cases where the warning system had no FAs. The effect of MR on the driving speed was significant ($F(2, 18) = 4.60$, $p < 0.05$). As seen in Fig. 5(a), the driving speed decreased as MR increased. Specifically, the driving speed when $\mathrm{MR} = 0.5$ was lower than the speed when $\mathrm{MR} = 0.25$ by 3.2 km/h on average, and the speed when $\mathrm{MR} = 1.0$ was lower than the speed when $\mathrm{MR} = 0.5$ by 3.7 km/h on average. When FAs were present ($\mathrm{MR} = 0.25$, $\mathrm{PPV} = 0.5$), the driving speed was lower by 2.3 km/h on average than the speed at the same MR but with no FAs ($\mathrm{MR} = 0.25$, $\mathrm{PPV} = 1.0$), though the effect of PPV on driving speed was not statistically significant.

As for the acceleration-pedal reaction time $\mathrm{RT_A}$ in Fig. 5(b), in the cases of $\mathrm{MR} = 0.25$, the reaction time to TP when $\mathrm{PPV} = 0.5$ was longer than that when $\mathrm{PPV} = 1.0$ by 0.29 s on average. If, instead, the acceleration-pedal reaction time is measured relative to the moment the warning began to display instead of the moment the pedestrian became visible to the driver, the difference in acceleration-pedal reaction time between the above two conditions is statistically significant ($t(9) = 2.82$, $p < 0.05$). No significant difference in $\mathrm{RT_A}$, when the system missed a pedestrian, was found among the four conditions. The mean response times for the missed-detection events (MS) was significantly greater than that of the true positive cases ($F(1, 9) = 102.1$, $p < 0.00001$). When warnings were present, even with a high miss or a low PPV, acceleration-pedal response occurred, on average, before the pedestrian was visible. In the miss cases, the subject only knew there was a pedestrian after passing the 75-m point, thus all responses occurred after that time.

In Fig. 5(c), with regard to brake-pedal reaction time $\mathrm{RT_B}$, in the cases of $\mathrm{MR} = 0.25$, the reaction time to TP when $\mathrm{PPV} = 0.5$ was longer than that when $\mathrm{PPV} = 1.0$ by 0.22 s on average.

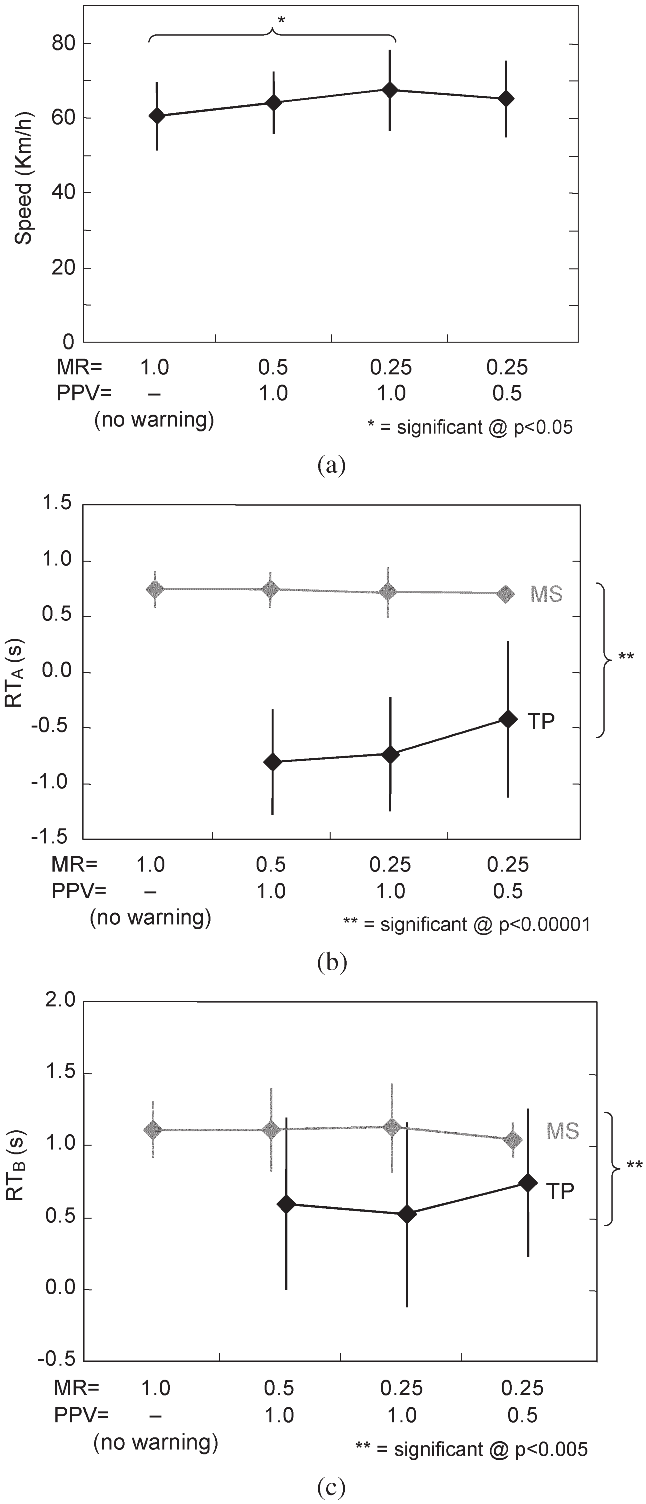


Fig. 5. Effect of warning accuracy on (a) driving speed, (b) acceleration-pedal reaction time, and (c) brake-pedal reaction time. Error bars represent standard deviations.

When the system missed a pedestrian, no significant difference in $\mathrm{RT_B}$ was found among the four conditions.

The mean driving speed was higher as MR decreased, supporting the hypothesis that the drivers relied more on the warning system when they perceived warnings to be more accurate. The reason why the reaction times $\mathrm{RT_A}$ and $\mathrm{RT_B}$ to TP were longer as PPV decreased at the same MR is thought to be that the drivers' trust in the warning decreased and the drivers tended to react more slowly. The difference in $\mathrm{RT_B}$ was not as significant as the difference in $\mathrm{RT_A}$, an effect thought to be due to the drivers' tendency to release the acceleration pedal based on a warning but to apply the brake pedal based on visual identification of a pedestrian rather than based on the warning. In miss cases, the driver was cued only by visual evidence of the pedestrian. The reason that the differences in $\mathrm{RT_A}$ and $\mathrm{RT_B}$ were not significant for the missed-detection cases is theorized to be that the drivers expected missed detections of the faulty warning system and paid greater attention to a visual view of a pedestrian. Finally, the reason for the lower driving speed at a smaller PPV with the same MR is theorized to be that the drivers compensated the decrease in safety margin due to the increase in the reaction times $\mathrm{RT_A}$ and $\mathrm{RT_B}$ by decreasing their driving speed. This supports the hypothesis that drivers tended to decrease their driving speed because of a reduction in their level of reliance.

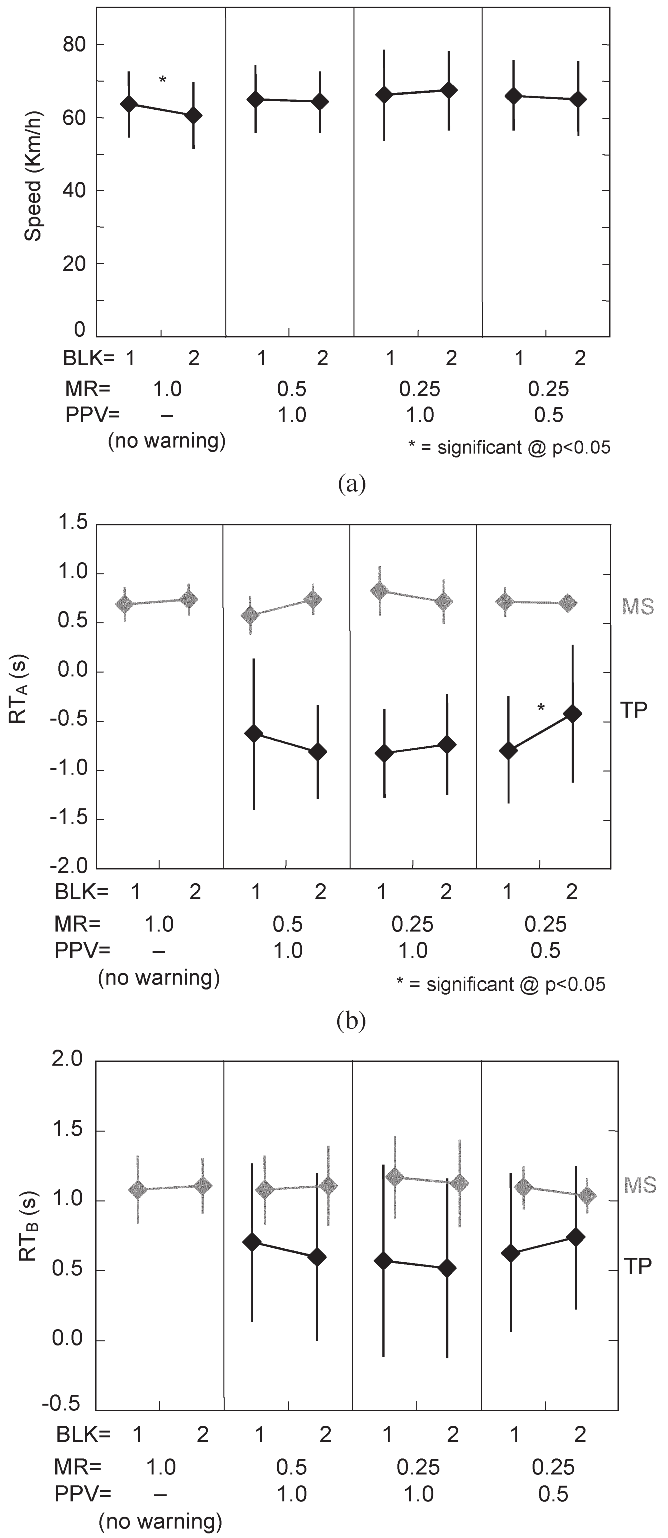
C. Learning Effects

Learning effects were observed between the first and second blocks during each scenario as the driver became accustomed to the quality of warnings being received. The learning effects on driving speed, acceleration-pedal reaction time $\mathrm{RT_A}$, and brake-pedal reaction time $\mathrm{RT_B}$, in terms of the difference between the first half $(\mathrm{BLK} = 1)$ and second half $(\mathrm{BLK} = 2)$ of the four test conditions, are shown in Fig. 6(a)–(c) respectively. The reaction times $\mathrm{RT_A}$ and $\mathrm{RT_B}$ to TP include only the cases in which a pedestrian crossed the road.

First, Fig. 6(a) shows the effect of learning on driving speed measured at the moment the car was 110 m from the pedestrian. When no warning system was used $(\mathrm{MR}, \mathrm{PPV}) = (1.0, -)$, the speed in the second block was lower than that in the first block by 3.1 km/h on average $(t(9) = 2.83,\ p < 0.05)$. With no warning system, it appears that the drivers learned that they could not drive rapidly and still safely avoid pedestrians. They therefore reduced their nominal driving speed slightly. For the other warning-system conditions, the difference in speed between the first block and second block was not significant.

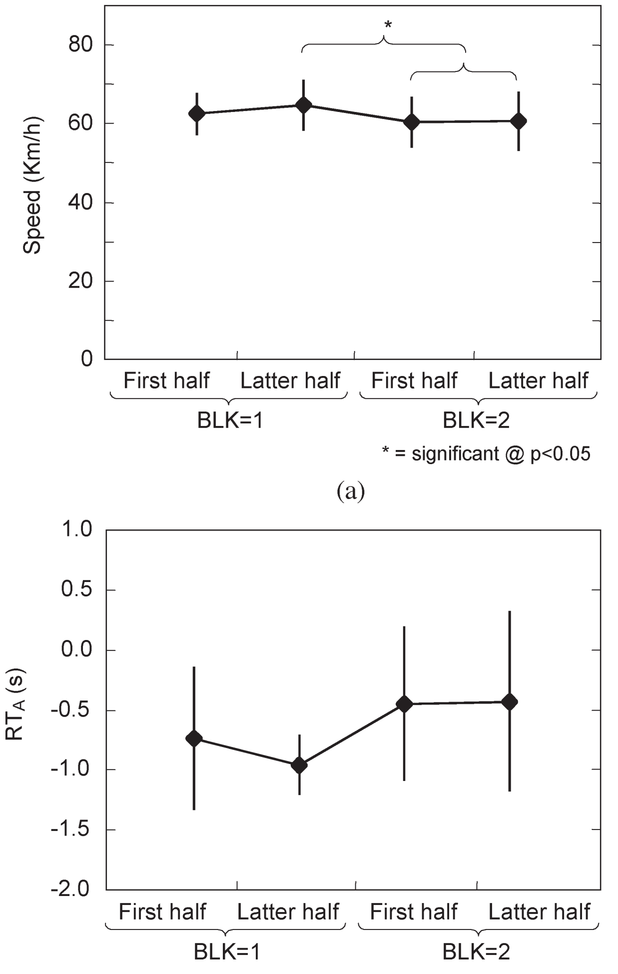
Next, Fig. 6(b) presents the acceleration-pedal reaction times $\mathrm{RT_A}$ for each warning-system condition and each block in the scenarios. When $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 0.5$, the reaction time to TP in the second block was larger than that of the first block by 0.37 s on average $(t(9) = 2.26, p < 0.05)$. It is believed that the lower PPV reduced the drivers' compliance with warnings, slowing their responses.

Finally, Fig. 6(c) presents the brake-pedal reaction times $\mathrm{RT_B}$. The difference between the first and second blocks was not significant in any condition for both the cases of TP and MS, although review of the outcome profile reveals similar trends to those of the acceleration pedal $\mathrm{RT_A}$. The reason why the difference in $\mathrm{RT_B}$ to TP when $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 0.5$ was not as significant as the difference in $\mathrm{RT_A}$ is thought to be that the drivers tended to apply the brake pedal based on visual identification of a pedestrian rather than based on the warning, as was shown in Fig. 4.



(c)

Fig. 6. Learning effect on (a) driving speed, (b) acceleration-pedal reaction time, and (c) brake-pedal reaction time.



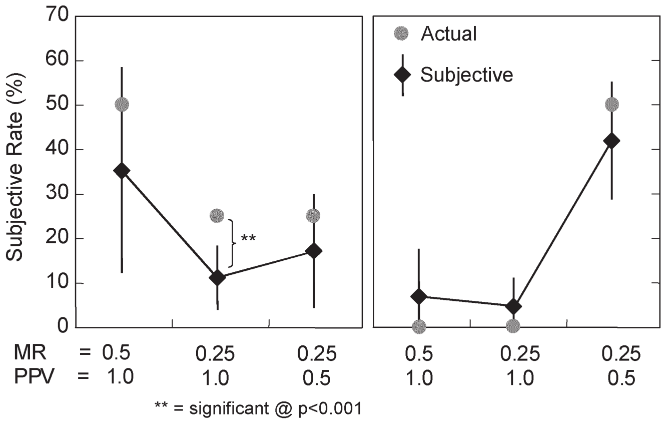
(b)

Fig. 7. (a) Learning effect by half block on driving speed when there was no warning and (b) acceleration-pedal reaction time when $(\mathrm{MR}, \mathrm{PPV}) = (0.25, 0.5)$.

Further analysis was conducted with regard to the conditions in which the learning effects were significant. The average driving speed when no warning system was used and average acceleration-pedal reaction time when $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 0.5$ by half block, that is to say quarter of a scenario, are illustrated in Fig. 7(a) and (b), respectively. Both of the driving speed and the acceleration-pedal reaction time have a similar trend; whereas the difference across the first three quarters was larger, the difference between the last two quarters, which corresponds to the second block, was smaller. This observation implies that the subjects became accustomed in the first block to the accuracy of the warning system in the short-term future.

D. Subjective Ratings

Fig. 8 illustrates the MR and FA ratio ($= 1 - \mathrm{PPV}$), comparing both the actual values and those estimated by the subjects. The average subjective MR estimated by the subjects was lower than the actual value across all conditions, as seen in Fig. 8(a). The difference between the subjective MR and the actual MR was 0.15 when $\mathrm{MR} = 0.5$ and $\mathrm{PPV} = 1.0$; 0.14 ($t(9) = 6.05$, $p < 0.001$) when $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 1.0$; and 0.08 when $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 0.5$. As seen in Fig. 8(b), the subjective FA ratio was lower than the actual FA ratio by 0.09 on average when $\mathrm{MR} = 0.25$ and $\mathrm{PPV} = 0.5$. These results imply that



(a) (b)

Fig. 8. (a) Actual and subject-estimated MR and (b) actual and subject-estimated FA ratio ($= 1 - \text{PPV}$).

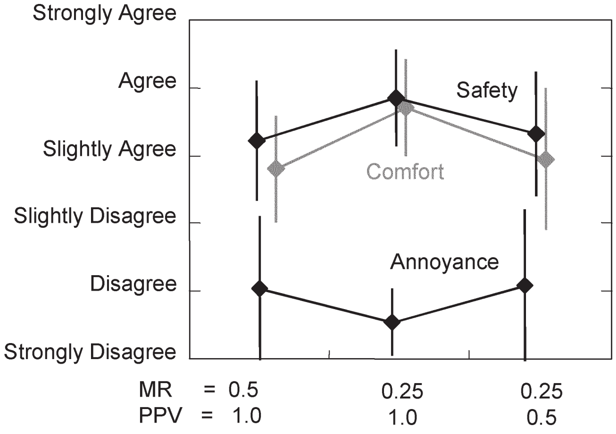


Fig. 9. Subject rating of the system in terms of safety, comfort, and annoyance.

drivers may be likely to estimate the MR and FA ratios of a warning system to be lower than the actual values. Even when the system had no FAs, however, subjects thought there might still be some residual FAs. The reason is thought to be that the drivers were likely to interpret a warning for a pedestrian who remained on the sidewalk as an FA, although the drivers had been told to only consider an FA as applying when a warning was given but no pedestrian appeared. It also may have been difficult for the subjects to form an accurate estimate of warning-system accuracy due to the limited number of runs that were performed.

Fig. 9 shows the ratings of the warning system by the subjects for three levels of warning accuracy in terms of safety, comfort, and annoyance level. The effect of warning accuracy on the safety rating was marginally significant ($p = 0.053$, Friedman test). The subjects rated the warning system when $\text{MR} = 0.25$ and $\text{PPV} = 1.0$ as being the safest for driving of the three levels of warning-accuracy conditions. The effect of warning accuracy on the subjects' comfort rating was marginally significant ($p = 0.054$, Friedman test). Of the three levels of warning accuracy, the subjects rated the warning system at $\text{MR} = 0.25$ and $\text{PPV} = 1.0$ as being the most comfortable for driving. The effect of warning accuracy on the annoyance rating was not significant, while the subjects rated the warning system when $\text{MR} = 0.25$ and $\text{PPV} = 1.0$ as being the least annoying of the three levels of warning accuracy that were tested.

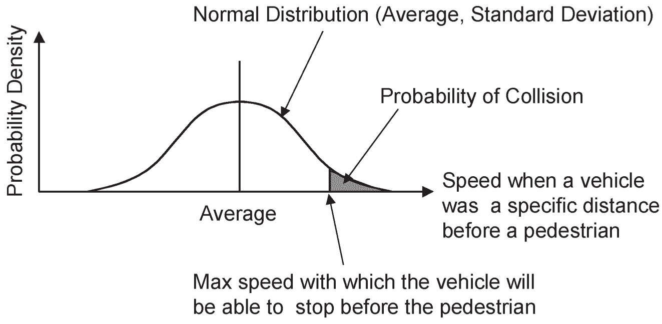


Fig. 10. Method for estimating the probability of collision.

E. *Effect on Safety*

The effect of the difference in the drivers' behavior on safety was investigated in terms of the resulting probability of collision with the pedestrians. To provide two alternate views, two different methods were used to estimate the probability of collision. First, we calculated the actual collision rate of the subjects in the experiment. In seven out of 160 crossing-pedestrian scenarios, there was a collision with a pedestrian. Due to small sample sizes, this estimate can only be considered to be an approximation of the true behavior, but it is a reflection of the actual driver's performance in the study. The other method of estimation used the observed average and standard deviation of vehicle speed when the vehicle was either 30 or 45 m from a pedestrian using the assumption that the speed was normally distributed, as shown in Fig. 10, based on a Kolmogorov–Smirnov test for a normal distribution of the speed. The maximum speed with which the vehicle was able to stop before a pedestrian was 66.1 km/h when the vehicle was 30 m before the pedestrian, and 80.8 km/h when the vehicle was 45 m before the pedestrian. By computing the probability that this speed would be greater than that from which a successful braking maneuver could be performed, we can estimate the probability of collision. This second method provides an estimate of collision risk based on the driving speed and the vehicle physics rather than the actual collisions that occurred in the experiment. The use of 30 and 45 m is arbitrary but a representative of the typical distances at which emergency braking could occur to avoid an obstacle in the roadway at the speeds used [27].

Table III shows the collision-probability results. Collision probabilities when TPs were given $P(C|\text{TP})$ and when the warning system missed a pedestrian $P(C|\text{MS})$, as well as the observed probability of collision $P(C)$, are shown for each test condition. As the table shows, the collision probabilities estimated with each of the three methods have a similar trend, as supported by a Chi-square test of the observed collision rate against that predicted analytically.

As Table III shows, when the warning system was the most accurate, the collision probability was not the smallest. The

TABLE III
ESTIMATED PROBABILITY OF COLLISION

Information Accuracy		Actual Collisions in the Experiment			Estimation from the Speed when the Vehicle was 30m from a Pedestrian			Estimation from the Speed when the Vehicle was 45m from a Pedestrian		
MR	*PPV*	*P*(C|TP)	*P*(C|MS)	*P*(C)	*P*(C|TP)	*P*(C|MS)	*P*(C)	*P*(C|TP)	*P*(C|MS)	*P*(C)
1.0	–		2/40	0.050		0.022	0.022		0.020	0.020
0.5	1.0	0/20	1/20	0.025	0.000	0.047	0.024	0.000	0.033	0.017
0.25	1.0	1/30	1/10	0.050	0.014	0.065	0.027	0.013	0.061	0.025
0.25	0.5	0/30	2/10	0.050	0.003	0.075	0.021	0.007	0.079	0.025

correlation coefficient between MR and the number of actual collisions in the experiment was -0.14, and the Spearman's rank correlation was not significant when no FAs were present $(\mathrm{PPV} = 0)$. This apparently inconsistent result is thought to be due to the risk compensation, wherein the driver becomes more careful as the quality of the warnings decreases. This may be a result of risk homeostasis: people may change their behavior in order to accept a certain level of perceived risk [28], though further studies and discussion are needed. The safest system may in fact not be the one where the warning system is the most accurate, as that could lead to overly aggressive driving that exceeds the safety actually imparted by the system.

In addition, as has been shown in Fig. 9, the subjects rated a system with lower MR as being safer, which is also inconsistent with the actual collision probability. The correlation coefficient between subjective rating in terms of safety (scaled between 1 and 6 as seen in Fig. 3) and the number of actual collisions in the experiment was 0.11, and Spearman's rank correlation was not significant. This highlights the importance of objective evaluation of the effect of a warning system on safety.

IV. CONCLUSION

Behavioral and safety effects of driver dependence on a warning system were investigated in a driving-simulator study. Warning-system accuracy was defined in terms of MR and PPV (PPV is the fraction of warnings that were correct detections). First, the driver behavior and performance were measured across four warning-system accuracy conditions. Second, the probability of collision in each accuracy condition was estimated and was used to measure the overall system effectiveness in terms of safety benefit. The major results of the experiment are summarized as follows: 1) as the MR increased, the mean driving speed decreased, showing a decrease in the driver's reliance on the warning system; 2) as the PPV decreased and the FA ratio increased, both the acceleration-pedal and brake-pedal reaction times became longer, showing a decrease in the driver's compliance with the warning system; 3) probability of collision did not increase, in general, with increased MR, suggesting that the drivers compensated for the changes in the warning-system accuracy; 4) when a pedestrian was missed by the system, subsequent differences in acceleration-pedal and brake-pedal reaction times were not significant regardless of the overall quality of the warning system being used. Experience with a faulty warning system in these cases did not appear to affect the reaction times.

This study applied the following methods to estimate the driver performance: 1) the degree of driver dependence on a warning system when no warning is issued, that is to say reliance, was evaluated by identifying an increase in baseline driving speed; 2) the degree of driver dependence on a warning, that is to say compliance, was evaluated by examining the acceleration pedal or brake-pedal reaction time; 3) effects on safety were evaluated using the estimated probability of collision, as well as actual collision rate, calculated from the average and standard deviation of observed speeds when the vehicle was a specific distance from an obstacle.

Other findings in this investigation include: 1) both the MR and FA ratios estimated by the subjects were lower than the actual values and 2) although the difference in collision probability was not statistically significant, the subjects felt that the system with the lower MR and higher PPV was safer than the other conditions.

It should be noted that the consequence of a collision with a pedestrian was low in this experiment. Needless to say, the cost of a collision with a pedestrian in the real world is extremely high. Therefore, the degree to which drivers would depend on an imperfect warning system is likely to be much smaller in a real-world case compared with what was observed in this experiment. It should be also noted that the effects investigated in this research are based on only 10-min driving segments and a longer driving experience may produce different effects—in particular, it might be difficult for subjects to accurately estimate FA rates based on such short exposure times. In addition, other factors such as age and personality of a driver, as well as road-environment conditions, warning timing, and warning modality, visual, auditory or tactile, may be relevant. Finally, the limited number of subjects and test runs used in this preliminary study limits the statistical power with which results can be interpreted and prevented complete counterbalancing of the test conditions. As a result, learning effects and warning-system effects may be confounded; a more thorough study would be required to fully separate these effects. Nonetheless, we believe that this limited investigation highlights some indicators of trends that may arise in a more complete study and can, therefore, be useful toward directing the design of future similar studies. The results also raise issues that should be considered by warning-system developers as they design and test new technologies for collision detection. Clearly, more research on the degree to which drivers depend on a warning system, using a more comprehensive experimental design beyond the preliminary study presented here, is warranted.

APPENDIX
GLOSSARY OF ABBREVIATIONS

BLK	Block number (1: first-half block, 2: second-half block, see Table I).
FA	False alarm (see Fig. 2).
MR	Miss rate (see Fig. 2).
MS	Miss (see Fig. 2).
$P(C)$	Probability of collision.
$P(C\|\text{TP})$	Probability of collision when the warning was true positive.
$P(C\|\text{MS})$	Probability of collision when the warning system missed a pedestrian.
PPV	Positive predictive value (see Fig. 2).
RT_A	Acceleration-pedal reaction time (see Fig. 4).
RT_B	Brake-pedal reaction time (see Fig. 4).
TP	True positive (see Fig. 2).

ACKNOWLEDGMENT

The authors would like to thank J. Meyer, T. B. Sheridan, K. Mitobe, I. Masaki, and J. F. Coughlin at the Massachusetts Institute of Technology AgeLab for their helpful advice on this study. They would also like to thank the anonymous reviewers for their valuable comments.

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