Collision Warning Timing, Driver Distraction, and Driver Response to Imminent Rear-End Collisions in a High-Fidelity Driving Simulator

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Rear-end collisions account for almost 30% of automotive crashes. Rear-end collision avoidance systems (RECASs) may offer a promising approach to help drivers avoid these crashes. Two experiments performed using a high-fidelity motion-based driving simulator examined driver responses to evaluate the efficacy of a RECAS. The first experiment showed that early warnings helped distracted drivers react more quickly – and thereby avoid more collisions – than did late warnings or no warnings. Compared with the no-warning condition, an early RECAS warning reduced the number of collisions by 80.7%. Assuming collision severity is proportional to kinetic energy, the early warning reduced collision severity by 96.5%. In contrast, the late warning reduced collisions by 50.0 % and the corresponding severity by 87.5%. The second experiment showed that RECAS benefits even undistracted drivers. Analysis of the braking process showed that warnings provide a potential safety benefit by reducing the time required for drivers to release the accelerator. Warnings do not, however, speed application of the brake, increase maximum deceleration, or affect mean deceleration. These results provide the basis for a computational model of driver performance that was used to extrapolate the findings and identify the most promising parameter settings. Potential applications of these results include methods for evaluating collision warning systems, algorithm design guidance, and driver performance model input.

INTRODUCTION

Rear-end collisions account for approximately 28% of all crashes, resulting in 157 million vehicle hours of delay annually, or roughly one third of all crash-caused delays (National Safety Council, 1996). Driver inattention has been identified as a contributing factor in over 60% of these crashes (Knipling et al., 1993). Because inattention is such a powerful contributor to rear-end collisions, rear-end collision avoidance systems (RECASs) may help resolve this problem.

Understanding how to mitigate dangers associated with inattention and distraction is becoming increasingly important because emerging technology has the potential to increase driver distraction (Lee, Caven, Haake, & Brown, 2001; Mollenhauer, Hulse, Dingus, Jahns, & Carney, 1997; Parkes, 1993). The possibility of increasing driving safety using RECAS has generated a substantial body of research (An & Harris, 1996; Dingus, McGehee, & Hankey, 1997; Hirst & Graham, 1997; Knipling et al., 1993). Although several RECASs are currently in development, substantial uncertainty exists regarding driver response to these systems and the effects they will have on driving safety (McGehee & Brown, 1998; Tijerina, 1998).

An important component of collision avoidance systems is the warning algorithm, which

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determines the timing of the warning; consequently, its design is as important as the design of the driver interface. A poorly timed warning may actually undermine driver safety (McGehee & Brown, 1998). An alert issued too early may be ignored by drivers if they are unable to perceive the cause of the warning. If an alert occurs too late, drivers may view it as ineffective, and a late alert may even disrupt an ongoing braking process. Understanding the influence of alert timing on driver response is crucial to estimating collision warning effectiveness.

The type of automation that a collision warning represents provides a theoretical basis for examining how alert timing might influence driver performance (Parasuraman, Sheridan, & Wickens, 2000). Although the type of automation is primarily dependent on its design, it also depends on the users' interpretation of the automation. For example, drivers might consider a collision warning system to be automation that acquires and analyzes information to specify an appropriate driver response (automation that triggers a response). Alternatively, drivers may view the same system as automation that simply detects abnormal events and alerts the driver (automation that redirects attention). Whether drivers view the collision warning system as automation that triggers a response or as automation that redirects attention can have important implications for design (Parasuraman et al., 2000).

A collision warning system that triggers a response is likely to generate an open-loop response that could neglect important considerations regarding surrounding traffic and the alert validity (Lee, Gore, & Campbell, 1999). In this situation, the false warning associated with algorithms that provide early alerts could undermine safety by triggering an inappropriate braking response. Viewed as automation that redirects attention, the collision warning system is likely to generate a closed-loop response. If this is the case, then braking is modulated according to how the traffic situation impinges on the driver's perception of the field of safe travel (Brown, Lee, & McGehee, 2000; Gibson & Crooks, 1938). If this is the case, then late alerts would provide a smaller safety benefit because drivers may not have enough time to interpret the driving situation and generate an appropriate response. These theoretical distinctions have important implications for algorithm design. If the collision warning system acts as automation that triggers a response, then a relatively late warning that minimizes false warnings might be the best design alternative. Conversely, if the collision warning system acts as automation that redirects attention, then early alerts would provide a greater safety benefit.

The fundamental objective of this research is to investigate the ability of a RECAS to enhance driver response to a situation involving an imminent collision. The two experiments described in this paper address this objective. The first experiment examines the effectiveness of the RECAS in alerting distracted drivers and how this effectiveness depends on the alert timing. The second experiment examines the benefits of a RECAS for drivers who are not distracted. To establish the generality of these findings, we examined these issues over a range of representative speeds, headways, and lead vehicle deceleration rates. These experiments include outcome measures to estimate the safety benefit of the warning and measures of the driver response process to understand the mechanisms by which RECAS warnings may enhance driver performance.

EXPERIMENT 1

Method

The purpose of the first experiment was to investigate how RECAS warnings affect distracted driver response to imminent rear-end collision situations – specifically, response to early and late warnings triggered under varying speed, headway, and deceleration conditions.

Participants. This experiment included 120 drivers between the ages of 25 and 55 years, with an equal number of male and female drivers. All were licensed drivers and had normal or corrected-to-normal vision. Each driver was paid $30 for the time taken to complete the experiment. None of the drivers had previously participated in any simulator or crash avoidance studies.

Apparatus. Data were collected using the Iowa Driving Simulator, which used complex computer graphics to produce a highly realistic automobile operating environment. Four multisynch projectors cast 190° forward field-of-view and 60° rear-view images onto screens surrounding an automobile cab. The cab and screens were mounted on a six-degree-of-freedom motion base to provide motion cues to the driver. The cab used in this study consisted of a fully instrumented 1993 Saturn four-door sedan. The vehicle dynamics and the antilock brake system were modeled for a Ford Taurus, a typical midsize American car. The Ford Taurus vehicle dynamics model was developed by the National Highway Traffic Safety Administration for use with the National Advanced Driving Simulator.

In addition to objective data quantifying the drivers' vehicle control inputs, four video cameras were used to record simulator events for analysis of driver behavior, response timing, and reaction to the incursion event. One camera focused on the throttle and brake pedals, another on the driver's face, and a third on the driver's hands on the steering wheel. The fourth camera recorded the forward view of the road scene. Both sensor data and video data were collected at a rate of 30 Hz.

Although several RECAS algorithms have been developed, the algorithm described by Burgett, Carter, Miller, Najm, and Smith (1998) shows promise and was used in our experiments. The algorithm has three free parameters: safety margin (SM), reaction time (RT), and deceleration of the following vehicle (d_F). SM represents the distance of the closest point of approach between the two vehicles, RT is the assumed reaction time of the driver of the following vehicle, and d_F is the assumed deceleration of the following vehicle. More specifically, RT is the time from the onset of the warning to the point when the driver begins to decelerate.

This study examined driver response to different values of the assumed deceleration (d_F) warning parameter to quantify the effects of this parameter on driver response and algorithm effectiveness. Brown, Lee, & McGehee (2001) presented a detailed description and analysis of the warning algorithm.

The RECAS display included an auditory warning and a visual icon. The auditory warning was composed of four sound bursts, each burst containing four pulses, and lasted approximately 2.25 s. Bursts were separated by 110 ms and pulses were separated by approximately 10 ms. The prominent frequency of the pulse was 2500 Hz. The ambient sound level caused by road and engine noise was 67 dBa at 35 miles/h (56.3 km/h) and 72 dBa at 55 miles/h (88.5 km/h). The sound level of the warning tone alone was 74 dBa. The icon was presented 38 inches (96.5 cm) in front of the driver just above the instrument cluster (6° below the driver's eye point). The icon depicted a vehicle colliding with the rear of another vehicle. Both the icon and the warning tone were developed and tested for forward collision warning (Kiefer et al., 1999; Lerner, 1991).

Experimental design. A five-factor ($2^4 \times 3$) experimental design, mixed between and within subjects, contrasted initial velocity (35 miles/h [56.3 km/h] rural road and 55 miles/h [88.5 km/h] freeway), order of initial velocity, first and second exposure to a collision situation, situation severity with respect to lead vehicle deceleration magnitude and the initial headway (two levels), and the warning algorithm, consisting of two d_F levels and a baseline condition (no collision warning device). The situation severity and warning algorithm were introduced as between-subjects variables, with a within-subject replication of the experiment at a different initial velocity. For example, if a driver experienced the first collision situation at 35 miles/h (56.3 km/h) he or she would experience a second collision situation at 55 miles/h (88.5 km/h).

The order of presentation was counterbalanced across drivers. The order of the initial velocity, situation severity, and warning algorithm were combined to yield 12 between-subjects conditions, each of which included 10 drivers, for a total of 120 driver trials. Table 1 contains a summary of the independent variables, and in Table 2 we define the specific experimental conditions. *Warning time* in Table 2 is defined as the elapsed time between when the lead vehicle begins to brake and when the warning is issued. *Warning range* and *warning range rate* indicate the relative distance and velocity between the vehicles at the time the warning is issued.

TABLE 1: Summary of Independent Variables and Their Levels for Experiment 1

Independent Variable	Conditions
Initial velocity (within)	56.3 km/h (35 miles/h) on a rural highway 88.5 km/h (55 miles/h) on a freeway
Situation severity (between)	Low severity, lead vehicle deceleration 0.40 g/initial headway 1.7 s High severity, lead vehicle deceleration 0.55 g/initial headway 2.5 s
Warning algorithm (between)	Baseline, no warning SM = 2 m, RT = 1.5 s, d_F = 0.75 g (late) SM = 2 m, RT = 1.5 s, d_F = 0.40 g (early)
Exposure (within)	First unexpected braking event Second unexpected braking event
Order of initial velocity (between)	Low velocity (rural highway) followed by high velocity (freeway) High velocity (freeway) followed by low velocity (rural highway)

Dependent variables. Three measures describe the potential safety benefit of the warning, and five measures describe the effects of the warning on the driver response process. The safety benefit measures quantify the effects of warnings with respect to collisions or collision potential. The first safety benefit measure is *collision,* which specifies whether or not the driver's vehicle actually struck the braking lead vehicle. The collision measure is dichotomous (i.e., 1 = *collision,* 0 = *collision was avoided*). A related measure is *collision velocity,* which specifies the severity of the collision as measured by the difference in the velocities of the two vehicles at impact. When no collision occurs, collision velocity is zero.

The third safety benefit measure is *adjusted minimum time to collision* (TTC), a continuous measure of the severity of the collision situation. The adjusted TTC is calculated using equations of motion to determine the time to collision if the vehicles continue to travel at their current relative position, velocity, and acceleration. A positive minimum adjusted TTC represents the safety margin available to the driver. If the vehicles collide, the adjusted TTC is calculated by dividing the collision velocity by the average deceleration to the point of collision, yielding a negative TTC value that reflects the severity of the collision. A negative minimum adjusted TTC represents how much sooner the driver would have needed to begin braking to avoid collision with the lead vehicle. The adjusted TTC complements the collision and collision velocity measures by indicating the safety benefit

TABLE 2: Experimental Conditions and Warning Timing

Condition	Initial Velocity (km/h)	Lead Vehicle Deceleration (g)	Initial Headway (s)	Algorithm Parameter	Warning Time (s)	Warning Range (m)	Warning Range Rate (m/s)
1	56.3	0.40	1.70	Baseline, no RECAS			
2	56.3	0.40	1.70	d_F = 0.40 g	0.07	26.58	0.27
3	56.3	0.40	1.70	d_F = 0.75 g	1.00	24.62	3.93
4	56.3	0.55	2.50	Baseline, no RECAS			
5	56.3	0.55	2.50	d_F = 0.40 g	0.33	38.83	1.77
6	56.3	0.55	2.50	d_F = 0.75 g	1.26	34.87	6.80
7	88.5	0.40	1.70	Baseline, no RECAS			
8	88.5	0.40	1.70	d_F = 0.40 g	0.12	41.75	0.46
9	88.5	0.40	1.70	d_F = 0.75 g	1.58	36.91	6.19
10	88.5	0.55	2.50	Baseline, no RECAS			
11	88.5	0.55	2.50	d_F = 0.40 g	0.06	61.44	0.36
12	88.5	0.55	2.50	d_F = 0.75 g	1.52	55.20	8.23

for those situations in which drivers avoid collisions as well as the severity of collisions that do occur.

Five measures characterizing the response process were used to explain how the collision warning influences safety benefits. An important aspect of the response process is the decomposed reaction time, which comprises three specific measures: accelerator release reaction time, accelerator-to-brake transition time, and brake-to-maximum brake transition time. *Accelerator release reaction time* measures the reaction time to the braking event or the reaction time to the warning. Reaction time to the braking event was calculated for each driver, whereas reaction time to the warning was calculated only for those drivers assisted by the RECAS. *Accelerator-to-brake transition time* specifies the time between driver release of the accelerator and application of the brakes. *Brake-to-maximum brake transition time* measures the time required by the driver to reach maximum deceleration after the initial depression of the brake pedal.

Braking profile is another important description of driver response and is characterized by mean deceleration and maximum deceleration. *Mean deceleration* is defined as the average deceleration of the vehicle from initial brake depression until the driver's vehicle stops, collides with the lead vehicle, or passes the lead vehicle. *Maximum deceleration* is defined as the peak deceleration between the beginning and end of the braking event. Collectively, these response measures provide a clear description of how the collision warning influences driver braking response.

Procedure. Upon arriving at the Iowa Driving Simulator facility, participants completed an informed consent form and were briefed on the operation of the simulator. They then completed a demographic survey. To reduce anticipation of rear-end crashes, a simulator evaluation ruse was used to induce an unalerted response: Participants were told that they were to evaluate the fidelity of the simulator and were asked to drive as they normally would. They were instructed to pay particular attention to the feel of the steering, accelerator pedal, brakes, and other vehicle controls, as well as to the realism of the traffic. Participants were then escorted to the simulator dome and briefed by the in-vehicle observer on how to assess simulator fidelity.

Each participant was given a 5-min practice drive, during which he or she was told that the vehicle ahead would brake and to brake to a stop behind the vehicle. Following the practice drive, participants drove two other short-road scenarios, each ending in an imminent collision situation in which the lead vehicle braked suddenly. One scenario began and ended on a rural highway, where drivers encountered a collision situation at an initial velocity of 35 miles/h (56.3 km/h). The second scenario began with rural highway driving. Drivers were then required to merge onto a freeway, where they subsequently encountered the collision situation at an initial velocity of 55 miles/h (88.5 km/h).

A secondary task was intermittently imposed to distract the driver's attention from the roadway. A digitized voice occasionally prompted the driver to press a button near the rearview mirror. Pressing the button activated a display above the mirror that presented a changing series of single-digit numbers at a rate of 4 Hz. The driver was asked to watch these numbers and report the number of times the digit *4* appeared. In the imminent collision situation, pressing the button simultaneously activated the numerical display and caused the lead vehicle to begin braking. In this manner, drivers were distracted at the same instant the imminent collision situation was initiated. The button-press and display-monitoring task provided a controlled – though somewhat artificial – exposure to the visual, motor, and cognitive distraction associated with in-vehicle information system interaction and was similar to tasks used in other driver distraction studies (Lamble, Laakso, & Summala, 1999; Summala, Nieminen, & Punto, 1996).

To prevent drivers from anticipating collision situations in association with pressing the button, the experiment included several other instances in which the drivers were prompted to perform the secondary task. Likewise, instances in which the lead vehicle did not brake suddenly were included to prevent the driver from associating a lead vehicle with an imminent collision situation.

The underlying premise of this experiment was that the secondary task reproduced the distraction conditions and behavior of a distracted driver at the time the lead vehicle initiated braking. To verify this assumption, driver glance behavior preceding the collision event was analyzed. Every videotape frame was coded for all collision situations to determine whether the driver was looking at the road, looking at the display, or in transition between the two. Drivers looked at the road more at higher speeds (46.1%) than at lower speeds (34.3%), $F(1, 106) = 13.05, p < .001$. In addition, drivers spent a greater proportion of time looking at the road during the second exposure to the imminent collision situation than during the first exposure – 44.9% versus 35.6%, respectively, $F(1, 106) = 8.51, p < .01$. Drivers adapted their behavior and reduced the attention they were willing to devote to the secondary task after the initial collision situation. These data show that the secondary task drew drivers' attention away from the road during the collision situation. Although drivers devoted a substantial amount of visual attention to the secondary task, they did not ignore the roadway, and they performed realistically in dividing their attention between the road and the in-vehicle task.

Prior to each imminent collision situation, the simulator "coupled" the participants' vehicle to the lead vehicle at a fixed headway. When the secondary task button was depressed, the vehicles were separated by a precise time headway specified in the experimental design. When the driver pressed the button, the lead vehicle braked at a constant deceleration, coming to an abrupt stop.

To ensure that drivers could use only braking as a response to imminent collisions, conditions were devised to discourage steering as a response. Opposing traffic on the rural highway and a shadow vehicle to the left of the driver on the freeway made steering around the lead vehicle difficult. Although steering can be an appropriate response to warnings, an important objective of this experiment was to evaluate the warning algorithm in the worst-case condition when only braking is possible. Drivers therefore were constrained solely to the use of brakes in avoiding collision with the lead vehicle.

Results

Driver data were tabulated to create a database containing information for 240 imminent collision situations. Some data elements were missing for four cases. For example, one driver released the accelerator before the lead vehicle began to brake, making it impossible to calculate a reaction time. Several other drivers were not pressing the accelerator at the time the warning sounded. For these drivers, it was possible to identify the time they removed their foot from the accelerator by examining the videotape and recording the time at which their foot began moving off the accelerator. A least-squares approach was used to estimate the missing data.

The data were analyzed using the SAS mixed linear model (MIXED) procedure. A description of the dependent variables associated with potential safety benefits of the RECAS is presented next and is followed by a description of the variables associated with the underlying response process.

Potential safety benefit of the RECAS. Figure 1 shows that the percentage of imminent collision situations ending in a collision, the collision velocity, and the adjusted minimum TTC provide convergent evidence regarding safety benefits of the RECAS. The warning reduced the percentage of collisions, $F(2, 108) = 16.07, p < .0001$. An early warning provided the greatest benefit, yielding a collision rate of 8.8%, whereas a late warning yielded a collision rate of 22.5%, as compared with a 45.5% rate for the baseline condition with no warning. Similarly, the warning reduced collision velocity, $F(2, 108) = 15.51$, $p < .0001$ (i.e., from 4.74 m/s in the baseline scenario to 1.68 m/s for the late warning and 0.88 m/s for the early warning scenarios). The minimum TTC also demonstrates a warning benefit, $F(2, 108) = 32.62, p < .0001$, in which a 2.79 s safety margin was obtained for the early warning as opposed to the 0.90 s and 0.09 s margins obtained for the late warning and baseline scenarios, respectively. Figure 1 presents the results of the post hoc comparisons; different letters indicate significantly different conditions.

Beyond the effect of the warning, the

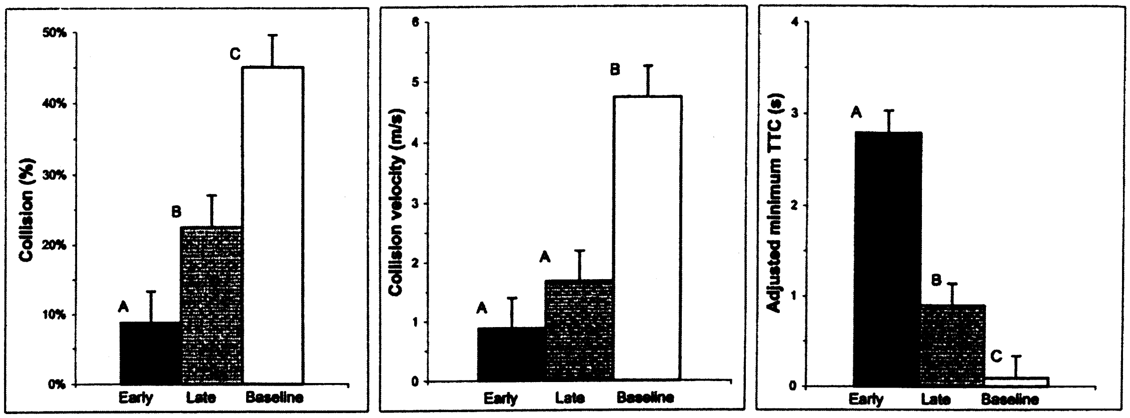

Figure 1. Safety benefit of early RECAS warning compared with late warning and baseline condition (no warning). Error bars represent one standard error.

severity of the collision situation and exposure to such situations exhibited a statistically significant effect on all three measures of safety. Not surprisingly, high-severity situations (2.50 s headway, 0.55 g deceleration) led to more collisions than did low-severity situations (1.70 s headway, 0.40 g deceleration; 30.4% vs. 20.4%, respectively), $F(1, 108) = 4.03, p < .05$; these situations also led to higher collision velocities (3.2 vs. 1.6 m/s), $F(1, 108) = 8.36, p < .005$, and to smaller minimum adjusted times to collision (0.87 vs. 1.65 s), $F(1, 108) = 7.96, p < .01$. Similarly, as expected, the first exposure resulted in more collisions than did the second exposure (38.3% vs. 12.5%), $F(1, 108) = 29.4, p < .0001$; it also resulted in higher collision velocities (3.6 vs. 1.3 m/s), $F(1, 108) = 19.33, p < .0001$, and smaller minimum adjusted times to collision (0.62 vs. 1.90 s), $F(1, 108) = 35.9, p < .0001$. No statistically significant interactions among the RECAS parameters, initial velocity, situation severity, order, and exposure were observed.

Response process: Reaction time and braking profile. Decomposing driver reaction times and examining driver braking profiles shows how the RECAS generates the observed safety benefits. Driver reaction time consists of (a) the time from the onset of braking by the lead vehicle to accelerator release, (b) movement time from accelerator release to initial brake depress, and (c) the time from the initial brake depress to maximum deceleration. A RECAS could generate the observed benefits by reducing any one of these components as well as by accentuating mean or maximum deceleration.

Figure 2 shows the effects of the RECAS warning on the driver response process. Examination of the experimental conditions in Table 2 shows a mean onset for the early warning of 0.145 s and a mean onset for the late warning of 1.34 s. This difference was reflected in driver reaction time, suggesting that drivers complied with the warning. Specifically, the warning influenced how quickly drivers released the accelerator in response to lead vehicle braking, $F(2, 108) = 47.4, p < .0001$. The early warning enabled drivers to react more quickly (1.35 s) than drivers with the late warning (2.10 s) or those with no warning (baseline condition, 2.21 s). The difference between the baseline and late warning failed to reach statistical significance. Consideration of how quickly drivers responded to the warnings showed that drivers released the accelerator more quickly in response to the late warning (0.76 s) compared with the early warning (1.14 s), $F(2, 72) = 23.38, p < .0001$, suggesting that for the late warning condition, drivers may have recognized the collision threat and begun responding before the warning triggered. The warning had no statistically reliable effect on the movement time from the accelerator to the initial brake press, $F(2, 108) = 0.23$.

Interestingly, the warning was associated with an *increased* time from the initial brake

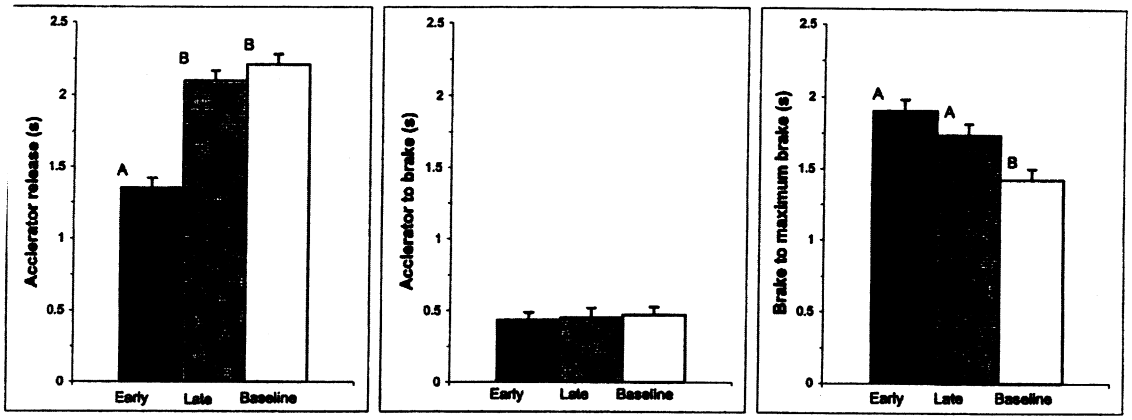

Figure 2. Effect of RECAS warnings on the response process.

press to maximum brake pressure, $F(2, 108) = 9.6$, $p < .0001$. Drivers in the baseline condition moved from initial brake press to maximum braking more quickly (1.42 s) than did drivers with the late warning (1.74 s) or early warning (1.91 s). This pattern of results seems to reflect a modulation of the braking response, in which drivers who respond early are able to brake in a more gradual manner. The warning did not have a statistically significant effect on mean deceleration, $F(2, 108) = 3.06$, $p > .05$, or maximum deceleration, $F(2, 108) = 0.93$, $p > .05$. The trend in mean deceleration shows that the late warning might be associated with a slightly greater mean deceleration (0.61 g) than the early (0.56 g) or the baseline (0.57 g) condition.

Beyond the effects of the warning, exposure to the collision situation also influenced drivers' braking response. The reaction time for accelerator release decreased from the first to the second exposure (2.11 vs. 1.67 s, respectively), $F(1, 108) = 39.52$, $p < .0001$. Warning reaction was also faster during the second exposure (0.74 s) than during the first exposure (1.16 s), $F(2, 72) = 43.71$, $p < .0001$. Similar to the effect of the early warning, the time from initial brake application to maximum braking increased slightly after the first exposure (from 1.61 s at first exposure to 1.77 s at second exposure), $F(1, 108) = 5.15$, $p < .05$.

Similarly, both the mean and maximum decelerations were higher during the first exposure compared with the second exposure. The mean deceleration was 0.60 g for the first exposure and 0.56 for the second, $F(1, 108) = 8.7$, $p < .01$. The maximum deceleration was 0.84 for the first exposure and 0.81 for the second, $F(1, 108) = 9.58$, $p < .01$. Together, these results suggest that drivers adjust their braking response depending on the evolving situation. A rapid initial response allows drivers to brake more gradually.

The severity of the situation also influenced driver response. The high-severity situation (2.50 s headway, 0.55 g deceleration) resulted in a longer mean accelerator release time (2.04 s) than did the low-severity situation (1.73 s; 1.70 s headway, 0.40 g deceleration), $F(1, 108) = 15.91$, $p < .0001$. This result parallels the effects of situation severity on collisions and collision severity: The more severe collision situation naturally resulted in more collisions.

Based on the data in Table 2, if drivers were to respond in a manner that exactly mimics the constraints embodied in the algorithms, they would release the accelerator and begin braking at 1.79 s for the high-severity situation and at 1.69 s for the low-severity situation. This response time is based on the mean warning time plus a 1.0 s reaction time. The 100 ms difference between the expected accelerator release time and the observed 310 ms difference indicates that drivers react more slowly than required in the more severe collision situation and compensate with a higher mean deceleration. The more severe situation led to a higher mean deceleration (0.60 *g*) compared with the less severe situation (0.55 *g*), *F*(1, 108) = 8.04, *p* < .01.

Cluster analysis of response patterns. Analyses of the safety benefits and the response process show the benefits of the RECAS and how those benefits are realized. These analyses do not, however, provide a holistic view of how these variables jointly characterize different ways of responding to imminent collision situations. Exploring the data with a cluster analysis provides a holistic perspective that reveals six patterns of collision outcomes and driver response. Table 3 shows the percentage of collisions, reaction times, and braking profiles for each of the six clusters. Using the SPSS k-means cluster analysis, we assigned each of the 236 events to one of the six clusters. Combinations of initial reaction time and maximum deceleration that maximize the difference in the adjusted TTC define the cluster centers.

The clusters in Table 3 are ordered by the adjusted minimum time to collision. Clusters 1 through 3 represent responses that generally avoid collisions, whereas Clusters 4 through 6 represent relatively ineffective response strategies. Interestingly, the mean deceleration is lower (0.54 *g*) for those clusters in which collisions tend to be avoided (Clusters 1–3). Conversely, the mean deceleration is higher for those clusters in which collisions are more likely to occur (0.64 *g* for Clusters 4–6). Examining the response pattern of the clusters in each of these groups shows how different response strategies and collision scenarios can lead to successful or unsuccessful outcomes.

Each of the six clusters is labeled according to the response pattern it represents. In Cluster 1, drivers released the accelerator early (1.12 s), followed by slow movement to the brake (0.63 s) and slow depression of the brake (2.83 s); thus Cluster 1 is characterized as an "early and slow" response. In contrast, drivers in Cluster 6 released the accelerator very late (3.00 s), followed by a fast movement to the brake (0.31 s) and very fast depression of the brake (0.83 s). Based on these characteristics, Cluster 6 can be termed "very late and very fast." The very rapid accelerator-to-brake movement time in Cluster 6 may reflect drivers' attempts to compensate for a late initial response. Each of the six clusters represents a substantially different response strategy in terms of event outcome and response process.

The membership of the six clusters indicates that the experimental conditions influenced

TABLE 3: Clusters and Their Characteristics that Describe Driver Response to Imminent Collision Situations

	Successful Clusters			Unsuccessful Clusters		
	1: Early & Slow	2: Early & Fast	3: Moderate & Fast	4: Late & Slow	5: Late & Fast	6: Very Late & Very Fast
Minimum TTC (s)	3.33	2.87	1.42	0.90	0.38	−1.84
% Collisions	0%	3%	11%	22%	39%	85%
Collision velocity (m/s)	—	—	5.8	5.4	7.7	12.1
Accelerator release (s)	1.12	1.20	1.69	2.30	2.28	3.00
Accelerator to brake (s)	0.63	0.50	0.42	0.41	0.43	0.31
Brake to maximum deceleration (s)	2.83	1.66	1.06	2.82	1.71	0.83
Mean deceleration (g)	0.56	0.54	0.53	0.64	0.65	0.61
Maximum deceleration (g)	0.83	0.82	0.79	0.87	0.87	0.81
Total events	26	61	38	23	54	34

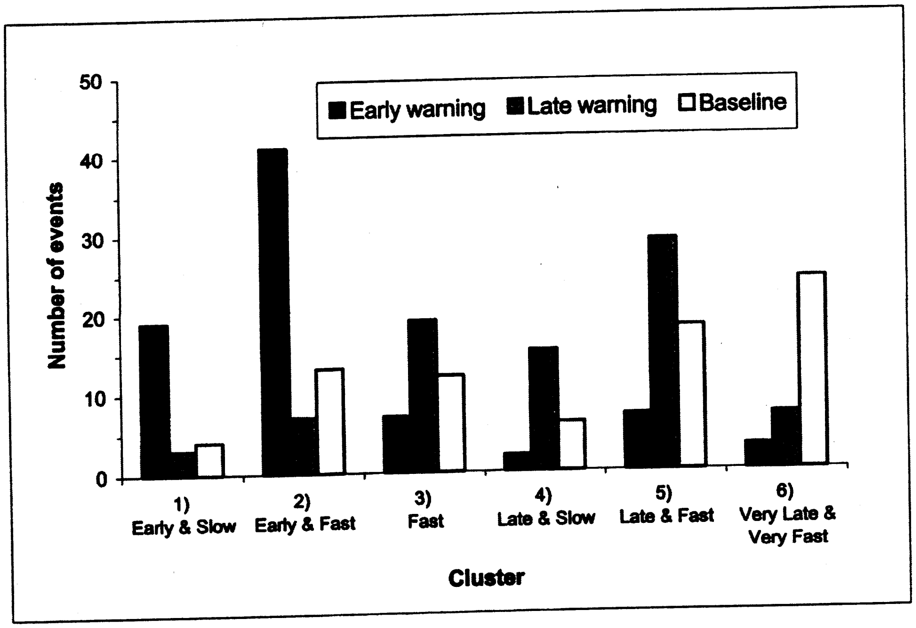

Figure 3. Effect of the timing and presence of the warnings on drivers' response strategies.

driver response strategies. As expected, the warning strongly influenced response strategies, $\chi^2(10) = 101.53$, $p < .0001$. Figure 3 shows this effect; Clusters 1 and 2 reflect compliance with the early warning and Clusters 3 and 4 reflect compliance with the late warning. Additionally, for baseline condition drivers, Clusters 2 and 3 reflect behavior that is consistent with the kinematic constraints embodied in the warning algorithms. Clusters 5 and 6 represent situations in which drivers failed to respond effectively to either warnings or perceptual cues indicating a potential collision situation. Interestingly, although Cluster 5 represents unsuccessful collision avoidance, this cluster is composed mostly of drivers who received the late warning, and it represents the largest concentration of these drivers.

Also interesting is that the severity of the collision situation did not have a statistically significant effect on the response strategy adopted by drivers, $\chi^2(5) = 10.35$, $p > .05$. Driver strategies were, however, highly dependent on initial velocity, $\chi^2(5) = 68.35$, $p < .0001$. Specifically, the Cluster 1 column of Table 4 shows that this cluster is composed almost entirely of drivers in the high initial velocity condition and reflects the onset of early warning (0.09 s) for the combination of early warning and high initial velocity conditions. This compares with the relatively late warning onset for the combination of early warning (0.20 s) and low initial velocity conditions, as reflected by the high proportion of these cases in Cluster 2.

The early accelerator release in Clusters 1 and 2 strongly reflects the benefits of the early warning. A similar pattern exists for Clusters 3 and 4. The relatively early accelerator release in Cluster 3 corresponds to the 1.13 s warning onset for the combination of late warning and low initial velocity conditions. This compares with the relatively late accelerator release in Cluster 4, which corresponds to the relatively late warning onset (1.55 s) associated with the combination of the late warning and high initial velocity conditions. Cluster 3 consists primarily of drivers subjected to low initial velocity conditions. Cluster 4 is composed entirely of drivers subjected to high initial velocity conditions. This pattern holds for those drivers who received a warning as well as for many who did not. Of the 61 events in Clusters 3 and 4, 18 represent the baseline condition in which a warning

TABLE 4: Distribution of Cluster Membership According to Initial Velocity and RECAS Warning

	Cluster					
	1: Early & Slow	2: Early & Fast	3: Moderate & Fast	4: Late & Slow	5: Late & Fast	6: Very Late & Very Fast
High initial velocity	24	21	5	23	28	16
Early	18	12	1	2	3	3
Late	3	2	2	15	14	4
Baseline	3	7	2	6	11	9
Low initial velocity	2	40	33	0	26	18
Early	1	29	6	0	4	0
Late	0	5	17	0	15	3
Baseline	1	6	10	0	7	15
Total events	26	61	38	23	54	34

was not given, suggesting that some drivers were sensitive to kinematic constraints in the absence of a warning.

In contrast to Clusters 1 through 4, Clusters 5 and 6 reflect responses that are not systematically affected by the timing of the warning onset or the other experimental conditions. The response profiles in these clusters do not depend on the experimental conditions. For example, in Cluster 5 approximately the same number of events occurred for the late warning under the high initial velocity condition (14) as for low initial velocity condition (15). The same holds true for the early warning and baseline conditions. This is in sharp contrast to Cluster 3, in which there are 17 late warning cases for low initial velocity conditions and only 2 for high initial velocity conditions. Likewise, this contrast is evident in Cluster 4, in which there are no instances of late warning for low initial velocity conditions and 15 for high initial velocity conditions. The severity and velocity experimental conditions did not exhibit a statistically significant effect on cluster membership for Clusters 5 and 6, $\chi^2(1) = 0.05$, $p > .05$, and $\chi^2(1) = 0.20$, $p > .05$. Interestingly, the drivers received a warning in more than half the events (46 of the 88) in these two clusters. These results can be interpreted as an indirect measure of driver compliance with the warning. Clusters 5 and 6 are indicative of drivers who did not comply with the warning.

If Clusters 5 and 6 represent drivers who ignored the warnings and were not attuned to the kinematic constraints of the situation, it could be expected that fewer drivers would be included in these clusters during their second exposure to the collision situations. Exposure to collision situations and experience with the RECAS should prompt more effective collision avoidance strategies. Figure 4 shows this to be the case: Cluster memberships shift as drivers become more experienced with the RECAS and the experiment, $\chi^2(5) = 18.14$, $p < .005$. The number of instances in Clusters 5 and 6 decreases 48.3% after exposure to the first collision event.

Discussion

The objective of this experiment was to investigate the effects of warning timing on driver response to imminent collision situations. The results address several aspects of this objective. First, the data demonstrate that RECAS warnings provide a substantial benefit, particularly if the warning is given early. Compared with no warning at all, an early RECAS warning reduces the number of collisions by 80.7%. Assuming that collision severity is proportional to kinetic energy, the early warning reduces collision severity by 96.5%. In contrast, the late warning reduces collisions by 50.0% and severity by 87.5%.

Second, the data identify how a warning affects the driver response process. RECAS aids drivers in avoiding collisions by speeding accelerator release, but it does not enhance any other aspect of the response. Drivers do not depress the brake more quickly or brake

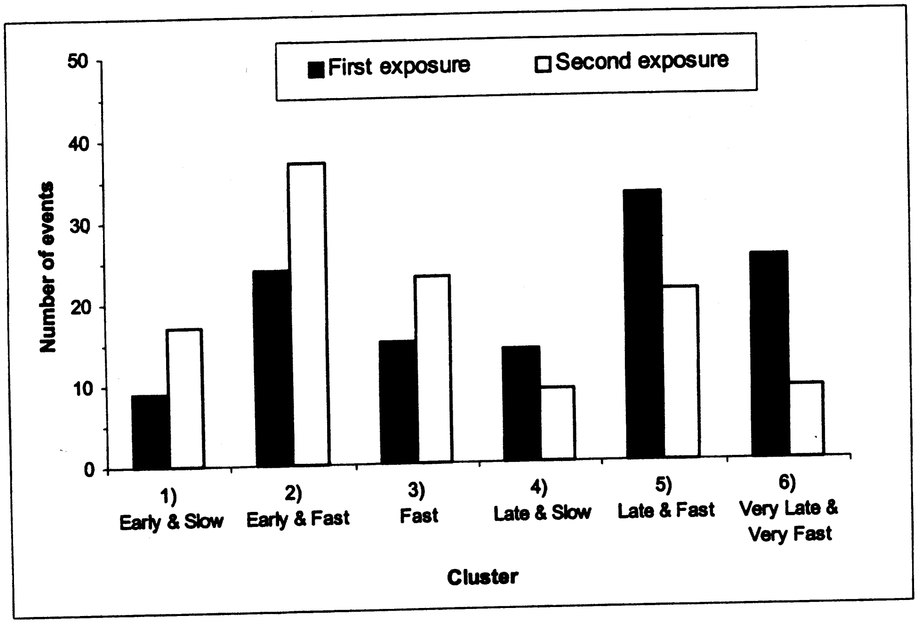

Figure 4. Effect of exposure to the collision event on the drivers' response strategies.

harder when they receive a warning. In fact, because compliance with the RECAS warning generated a faster accelerator release, drivers were able to brake more gradually. The difference in mean deceleration suggests a potential indirect benefit of the warning: less abrupt deceleration may decrease the risk of being struck from the rear, a common occurrence when abrupt deceleration of one vehicle triggers a multiple-car crash.

Exploratory analysis identified six clusters of collision avoidance responses. Four clusters reflect driver attunement to combinations of lead vehicle deceleration, initial headway, warning timing, and initial velocity. The remaining two clusters reflect the behavior of drivers who are not attuned to the warnings or the driving environment. Although many of these drivers were not given a warning, some who did receive a warning failed to respond appropriately, demonstrating that although a warning can aid drivers, it will not enhance performance if it is ignored.

It is surprising that some drivers seemed to ignore or discount the warning, given that the warnings always accurately indicated a collision situation. One possible explanation is that some drivers did not fully understand the nature and purpose of the warning. Another is that some drivers did not trust the warning and so discounted it (Lee & Moray, 1992, 1994). If distrust led drivers to ignore the warnings, then nuisance alarms that occur in an actual vehicle are likely to increase the number of drivers who discount the warning. Distrust associated with repeated exposure to nuisance alarms could substantially undermine RECAS effectiveness. Understanding the cause of poor compliance may be critical in developing an effective collision warning system.

Although the algorithm did not enhance any aspect of driver response other than initial accelerator release, responses were sensitive to the initial velocity and severity of the collision situation. For example, movement time from the accelerator to the brake was sensitive to the initial velocity. At lower velocities, drivers seemed to misestimate the need to brake because of the greater distance between vehicles. Likewise, drivers responded poorly to long headway and high deceleration conditions, which may reflect the relatively poor visual cues available to drivers in these situations (Hoffmann & Mortimer, 1996). Drivers compensated for their delayed accelerator release with a faster transition time from the accelerator to the brake and a faster transition from initial brake application to maximum deceleration. This compensatory behavior and the sensitivity of drivers' ongoing responses to these conditions indicates that drivers modulate their responses according to the evolving situation, suggesting that braking is not an open-loop process.

The results show that a collision warning affects the speed of accelerator release and that the remainder of the braking process is governed by visual and haptic cues in a closed-loop manner. The data suggest that the RECAS influences driver behavior by redirecting attention rather than triggering a braking response. Understanding the mechanism by which RECAS enhances driver collision avoidance behavior will enable the development of more accurate computer models for identification of appropriate RECAS parameters. These models can evaluate a wide range of algorithm parameters, which would not be feasible with simulator, on-road, or test track experiments (Brown et al., 2001).

Although this experiment generated important insights into the potential benefits of RECAS warnings, several issues were left unresolved. The experiment did not address the benefits RECAS might provide to drivers who are not distracted. Undistracted drivers who receive a warning might not benefit from it, and they might even be adversely affected should the warning distract them from an appropriate response to the lead vehicle. The effect of warnings on the response of undistracted drivers is a particularly critical issue from the perspective of estimating the benefits of RECAS. Experiment 2 addresses this issue.

EXPERIMENT 2

Method

The objective of the second experiment was to investigate driver response to imminent collision situations when *not* distracted at the onset of the collision situation. The apparatus and experimental protocol were the same as in the first experiment, except that the secondary task was eliminated.

Participants. Data were collected from 20 additional drivers 25 to 55 years of age. Inclusion criteria were the same as in Experiment 1.

Experimental design. Rather than being a complete replication of Experiment 1, Experiment 2 focused on a subset of the experimental conditions – specifically, the low-severity and early warning conditions. These conditions were chosen because they exhibited the lowest variance in Experiment 1 and, thus, were expected to provide the basis for the most sensitive statistical comparisons. The data from undistracted drivers were compared with data collected under the same conditions in Experiment 1. Table 5 shows the experimental conditions considered in Experiment 2. Ten drivers were included in the undistracted baseline condition, and 10 drivers were included in the undistracted early warning condition. Data for 20 distracted drivers in the baseline and early warning conditions from Experiment 1 were used for comparison.

TABLE 5: Experimental Conditions to Compare the Benefit of the RECAS for Distracted and Undistracted Drivers

Condition	Initial Velocity (km/h)	Lead Vehicle Deceleration (g)	Initial Headway (s)	Algorithm Parameter	Distracted by Secondary Task
1	56.3	0.40	1.70	Baseline, no RECAS	Yes (Exp. 1 data)
2	56.3	0.40	1.70	$d_F = 0.40$ g	Yes (Exp. 1 data)
3	88.5	0.40	1.70	Baseline, no RECAS	Yes (Exp. 1 data)
4	88.5	0.40	1.70	$d_F = 0.40$ g	Yes (Exp. 1 data)
5	56.3	0.40	1.70	Baseline, no RECAS	No
6	56.3	0.40	1.70	$d_F = 0.40$ g	No
7	88.5	0.40	1.70	Baseline, no RECAS	No
8	88.5	0.40	1.70	$d_F = 0.40$ g	No

Results

Data from each driver were combined to form a database of 80 imminent collision situations. Of these, some data elements were missing for three cases. For example, one driver released the accelerator before the lead vehicle began to brake, making it impossible to calculate a reaction time. The data were analyzed using the SAS MIXED procedure. Dependent variables associated with potential RECAS safety benefits are described next, followed by a description of the variables associated with the underlying response process.

Safety benefit of the RECAS. The percentage of imminent collision situations ending in collision, collision velocity, and minimum adjusted TTC show that RECAS provides a safety benefit to both distracted and undistracted drivers. The warning reduced the percentage of collisions, $F(1, 52) = 20.17$, $p < .001$. With the early warning, collisions were reduced to only 1.4% of collision situations, compared with 26.0% in the baseline condition. This effect interacted with whether or not drivers were distracted; drivers who received a warning avoided most collisions regardless of whether or not they were distracted, $F(1, 52) = 4.95$, $p < .05$. Figure 5 shows that collisions occurred for undistracted drivers 14.2% of the time without a warning and 0.7% of the time when a warning was given. In comparison, collisions occurred for distracted drivers 37.9% of the time without the warning and 2.1% of the time when a warning was given. Overall, distracted drivers were involved in more collisions (20%) than were undistracted drivers (7.4%), $F(1, 52) = 6.34$, $p < .05$.

The warning also reduced collision velocity, $F(1, 52) = 11.36$, $p < .01$; without a warning, drivers collided at 2.1 m/s, compared with 0.1 m/s for drivers who received a warning. In addition, the warning also increased the minimum adjusted TTC, $F(1, 52) = 38.40$, $p < .001$; without a warning, drivers had a minimum adjusted TTC of 1.0 s, compared with 3.5 s for drivers who received a warning. For both collision velocity and adjusted minimum TTC, the interaction between distraction and warning did not reach statistical significance, suggesting that the warning similarly benefits undistracted and distracted drivers. The data provide no evidence to suggest that providing undistracted drivers with a collision warning could degrade driving safety.

In addition to the effect of RECAS warnings with respect to driver distraction, several other interesting effects were identified. As in Experiment 1, the percentage of imminent collision situations ending in collision, collision velocity, and minimum adjusted TTC show that performance improved after the first exposure to the collision situation. On their second exposure, drivers were less likely to collide, $F(1, 52) = 16.43$, $p < .001$. Specifically, drivers collided in 24.6% of the initial collision situations, compared with 2.9% during the second exposure. Drivers also exhibited lower

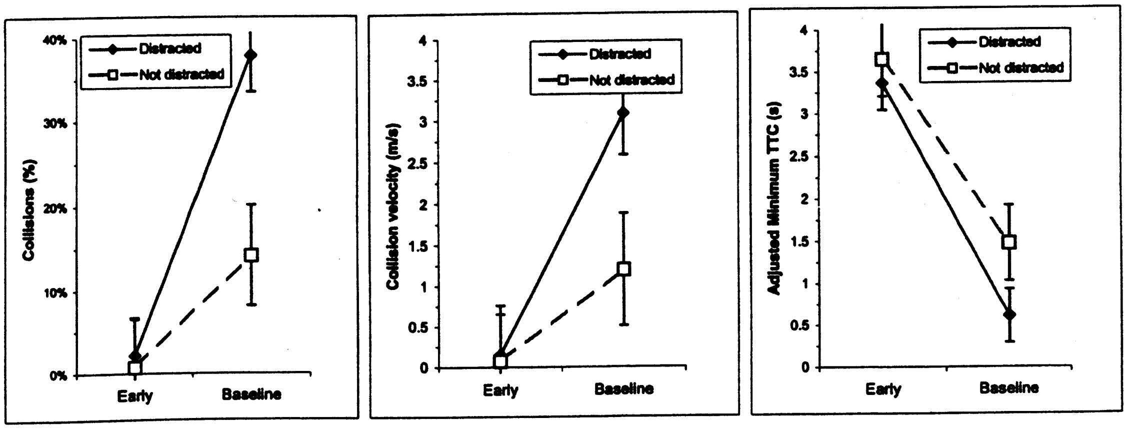

Figure 5. Effect of RECAS warning and distraction on safety.

collision velocities after the first exposure, $F(1, 52) = 11.89$, $p < .01$. Collision velocity was 1.9 m/s during the first exposure, compared with 0.3 m/s during the second exposure. The minimum adjusted TTC was also larger for the second exposure than for the first, as demonstrated by the increase in the safety margin from an adjusted TTC of 1.7 s in the first exposure to 2.9 s in the second exposure, $F(1, 52) = 15.59$, $p < .01$.

The effect of exposure on the percentage of collisions and on collision velocity is complicated by an interaction with the RECAS warning, $F(1, 52) = 11.76$, $p < .01$, $F(1, 52) = 8.47$, $p < .01$. When no warning was given, drivers collided 46.0% of the time with a collision velocity of 3.6 m/s during the first exposure and 6.0% of the time with a collision velocity of 0.7 m/s during the second exposure. When a warning was given, drivers collided 3.1% of the time in the first exposure with a collision velocity of 0.2 m/s and experienced no collisions in the second exposure.

This interaction reflects a floor effect: There was less room for improvement from the first to the second exposure for the early warning group compared with the baseline. The order in which drivers experienced the high- and low-velocity collision situations affected the overall chance of collision. Drivers exposed first to the high initial velocity situation experienced more collisions (19.3%) than did drivers who experienced the low initial velocity condition first (8.2%), $F(1, 52) = 4.08$, $p < .05$. It appears that drivers were better prepared for subsequent occurrences when first exposed to the high-velocity collision scenario as opposed to the low-velocity scenario.

Response process: Reaction time and braking profile. RECAS warnings and distraction also affected drivers' response to the collision situation. Figure 6 shows the effect of distraction and RECAS warning on driver reaction time. The warnings increased the speed of accelerator release, $F(1, 52) = 64.22$, $p < .0001$. Drivers who received a warning released the accelerator in only 1.03 s, compared with 1.73 s for the baseline scenario. Distracted drivers released the accelerator later in response both to lead vehicle braking, $F(1, 52) = 24.36$, $p < .0001$, and to warning onset, $F(1, 26) = 5.82$, $p < .05$; they required 1.59 s to respond to the lead vehicle and 1.04 s to respond to the warning. In contrast, undistracted drivers required only 1.16 s to respond to the lead vehicle and only 0.76 s to respond to the warning.

As shown in Figure 6, neither warning nor distraction affected the transition time from accelerator to brake. The warning did increase the time between initial brake press and maximum deceleration, however, $F(1, 26) = 5.54$, $p < .05$. Given a warning, drivers moved from initial brake application to maximum brake application in 1.96 s, compared with 1.62 s for no warning. In contrast, distracted drivers depressed the brake faster than did undistracted drivers, $F(1, 52) = 5.71$, $p < .05$.

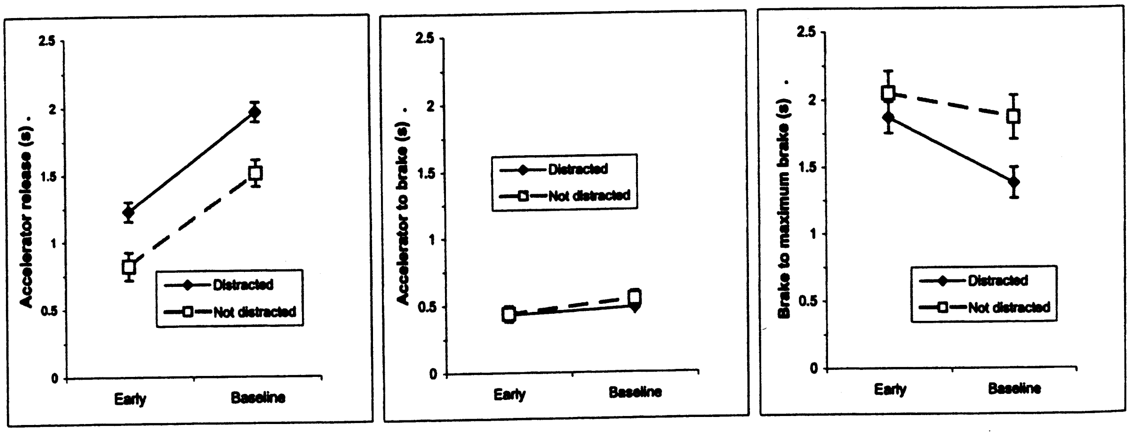

Figure 6. Effect of distraction and RECAS warnings on the response process.

Distracted drivers transitioned from brake press to maximum brake in 1.62 s, whereas the transition for undistracted drivers required 1.96 s. The warning did not interact with driver distraction for any element of the response process, suggesting that the warning enhances driver response, as it enhances the safety benefit, independent of distraction.

The warning interacted with initial velocity to influence transition time between the accelerator and the brake, $F(1, 52) = 9.25, p < .01$. The initial velocity affected the transition from accelerator to brake only in the baseline condition. When drivers were given no warning, the transition time was 0.69 s for the higher initial velocity and 0.34 s for the lower initial velocity. When a warning was given, transition times were nearly equal: 0.44 and 0.42 s for the high and low initial velocities, respectively. Interestingly, no interaction between warning and distraction occurred for accelerator release, $F(1, 52) = 0.05, p = .824$, or for the transition from brake to maximum brake, $F(1, 52) = 1.22, p = .274$.

In addition to RECAS warnings and driver distraction, exposure, initial velocity, and order also affected driver response. The second exposure to the collision scenario reduced driver reaction time both to the event, $F(1, 52) = 10.36, p < .005$, and to the warning, $F(1, 26) = 9.99, p < .005$. Drivers released the accelerator 1.53 s after the lead vehicle began to brake and 1.03 s after the warning during the first exposure, compared with 1.22 and 0.75 s, respectively, for the second exposure.

Higher initial velocity led to longer accelerator-to-brake transition times, $F(1, 52) = 10.91, p < .001$. For the lower initial velocity, drivers required 0.39 s to transition from the accelerator to the brake, whereas for the high initial velocity, 0.56 s was required. Similarly, initial velocity affected the time to transition from initial brake application to maximum deceleration, $F(1, 52) = 25.80, p < .0001$. For the lower initial velocity, drivers required 1.51 s to transition from brake to maximum brake, whereas for the high initial velocity, 2.08 s was required.

Accelerator-to-brake transition time was also affected by the order in which drivers were exposed to high and low initial velocity conditions, $F(1, 52) = 5.31, p < .05$. Drivers who first experienced the high-velocity condition exhibited a mean transition time of 0.54 s, whereas the mean transition time for drivers who first experienced the low-velocity condition was 0.41 s. In the high-velocity scenario, the lead vehicle is farther away and perceptual cues are not as salient; consequently, braking is slightly delayed. These results suggest that the warning directs driver attention to the collision situation and that the response process is mediated by perceptual cues, not the warning.

Deceleration was affected by both initial velocity and exposure. For low initial velocity, drivers had a greater average deceleration, $F(1, 52) = 6.64, p < .05$, and greater maximum deceleration, $F(1, 52) = 6.34, p < .05$. In the rural road scenario, drivers decelerated at an average of 0.55 *g* with a maximum deceleration of 0.81 *g*. In comparison, for the high initial velocity condition, drivers decelerated at 0.49 *g* with a maximum deceleration of 0.77 *g*.

Maximum deceleration was also influenced by exposure, $F(1, 52) = 4.10, p < .05$. On the first exposure, drivers' maximum deceleration was 0.81 *g*, compared with 0.77 *g* on the second exposure. These results parallel the findings from the first experiment and show that drivers adjust their braking behavior according to the evolving situation. Drivers who brake early brake more moderately.

A detailed analysis of drivers' accelerator and brake pedal responses during warning onset was conducted by examining graphs of the responses. Very few graphs exhibit any change in driver response during or immediately following warning onset. Four drivers released the accelerator close to the warning onset (i.e., within 100 ms). One driver released the accelerator abruptly when the warning began to sound. Two drivers abruptly depressed the accelerator during the initial moments. Given that these responses represent less than 5% of the total, these data suggest that "startle" responses during nonbraking behavior are unlikely.

In addition, it is difficult to determine whether the warning caused the accelerator movement or these responses simply coincided with the warning. Moreover, only one of these drivers experienced a collision, and it was minor, suggesting that the warning did not impede response. When the warning sounded, only two drivers (out of 280 trials) were already braking. One driver had begun to release the brake pedal, and so when the warning sounded, this driver was able to rapidly depress the pedal. The warning appeared to have no effect on the other driver. Because so few drivers received a warning as they were braking, the data do not provide a good basis for evaluating how the warning might disrupt an ongoing response.

Discussion

The objective of this experiment was to examine the effects of the RECAS warning on drivers who were not distracted. The results indicate that drivers benefit from the warning regardless of whether or not they are distracted. No interaction occurred between distraction and warning except when floor effects were encountered (i.e., the percentage of collisions cannot be less than 0%), suggesting that undistracted drivers benefit from the warnings as much as distracted drivers do. Both distracted drivers and undistracted drivers responded faster with the warning and maintained a greater safety margin. The data do not indicate that a warning might undermine safety for an undistracted driver.

Figure 7 shows the relative benefit associated with the warning. The RECAS warning had the most significant effect, followed by distraction and exposure. The absolute magnitude of the differences indicates that having the warning is more beneficial than either not being distracted or experiencing the collision event for a second time. These results provide strong evidence that warning drivers even when they are not distracted can have substantial benefits in imminent collision situations.

GENERAL DISCUSSION

This study provides guidance regarding algorithm design, supports development of driver performance models, and contributes to methods for evaluating collision warning systems. These contributions depend on how well driver behavior in a simulator generalizes to on-road driving. Because this study was conducted in a simulator, drivers were not exposed to the same risk as on a roadway. Although the lack of severe consequences in the simulator could have affected driver behavior, informal observations suggest that drivers were fully

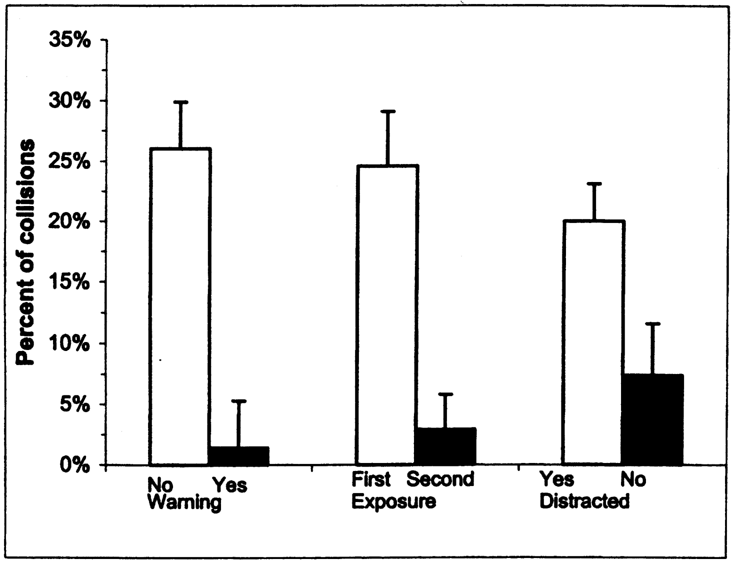

Figure 7. The relative effect of RECAS warnings, distraction, and exposure.

engaged and immersed in driving and that they reacted as though they were in an actual collision situation.

Another important caveat of this study is that drivers were exposed to the collision warning system for approximately 30 min and were not exposed to nuisance alarms. The nuisance alarms that would probably accompany long-term exposure could potentially undermine the observed safety benefits.

Finally, the experiments considered only a limited range of collision situations, algorithm parameters, and driver interface options. In particular, the study exposed drivers to severe situations. In normal driving, such situations are rare – the overrepresentation of them in these experiments should be considered in extrapolating the results and estimating crash reduction benefits for the driving public. Thus care is required in extrapolating to general design considerations. Even given these caveats, the study has important implications for system design and future research.

Design Recommendations

The results show that a RECAS can substantially reduce the chance of collision in the scenarios tested. Not surprisingly, an early warning is of greater benefit than a late warning; however, the operational implications of this benefit depend on how much the early-warning algorithm increases nuisance alarms. The data show that drivers respond to collision warnings as automation that redirects attention rather than as automation that triggers a response. If the warning triggered a response, then the warning might have enhanced accelerator release response, decreased transition time from accelerator to brake, decreased the time between initial brake depression and maximum deceleration, and increased mean and maximum deceleration. The data from both experiments, however, show that an enhanced accelerator release response is the only warning effect. The warning appears to affect driver response by redirecting driver attention to the road. Consequently, the benefits of early warnings in providing drivers with additional time to interpret and respond to the situation probably outweigh the costs associated with inappropriate braking responses to nuisance alarms. A large number of nuisance alarms might undermine driver acceptance but are unlikely to generate inappropriate braking responses.

The large potential safety benefit observed for distracted drivers constitutes preliminary evidence supporting the use of a RECAS to aid drivers distracted by in-vehicle technology (e.g., cellular telephones). The potential safety benefits of this system will probably increase as in-vehicle information systems proliferate and increase driver distraction. Algorithm designers might consider adjusting the warning threshold based on an estimate of driver distraction, such as the state (in use/not in use) of a cellular telephone. Such a strategy might provide particularly large safety benefits.

This study clarified the nature of driver response to rear-end collision warnings in a manner that can support model development. The data show that the warning affects only the initial release of the accelerator and affects neither the time required for a driver to move his or her foot to the brake pedal nor the degree of brake pressure. The results also indicated that drivers modulate their braking responses according to the evolving situation. Drivers who release the accelerator early brake more moderately than do those who release it late. This closed-loop response is an important component of an accurate driver model.

The data also provided preliminary evidence regarding the switching time associated with transitioning from the distraction task to the collision avoidance response. In broadening understanding of the mechanisms by which collision warnings affect braking behavior, this research directly contributes to the development of more precise computational models of driver behavior that can help to evaluate RECAS effectiveness.

The results have enabled the development of a computer model that can extrapolate results and identify promising parameter settings. The model, the attention-based rear-end collision avoidance model (Brown et al., 2000), is largely based on Gibson's field theory of driving (Gibson & Crooks, 1938) and provides a theory-based extrapolation of experimental results. Using this model, it is possible to extend the analysis beyond the circumstances tested in the simulator to identify parameters that are likely to provide the greatest safety benefit. The first experiment examined only two combinations of assumed deceleration and reaction time. A 1.5 s assumed reaction time was combined with 0.40 and 0.75 *g* assumed deceleration. The model-based analysis examined levels of assumed driver reaction time from 1.0 to 2.0 s in 0.25 s increments while varying assumed deceleration from 0.20 to 0.75 *g* in 0.05 g increments. The speed and situational severity values were the same as those used in the simulator study.

Figure 8 shows a contour plot of the percentage of collisions for each combination of algorithm parameters. The probability of a collision is greatest when high assumed decelerations are paired with low assumed reaction times. The combination of a 1.5 s assumed reaction time and 0.40 *g* assumed deceleration shows promise. Areas with high probability of collision are not close to this area. Although other regions of low probability of collision could be examined, areas closest to the higher rates of collision could be more susceptible to inaccuracies in the model and to variations in the driving situation. Further model-based analysis should be conducted to identify how the parameters affect false alarms. Creating an objective function that reflects both the costs of false alarms and the benefits of collision detection will enable the creation of a similar contour to help in identifying optimal algorithm parameters.

This study also provides data regarding approaches to evaluating collision warning systems. Evaluation of collision warning systems poses a challenge because collision events happen rarely and because repeated exposures in a short period are not representative of the driving context. This study used repeated exposures to collision situations to evaluate RECAS warning effectiveness.

Three criteria provide a basis for evaluating the utility of this approach. The first and most important criterion for evaluating the validity of multiple exposures is the interaction between exposures and RECAS conditions. The data show no interactions. The second criterion concerns the effects of exposure on the dynamics of driver response. The data show that subsequent exposures induced drivers to

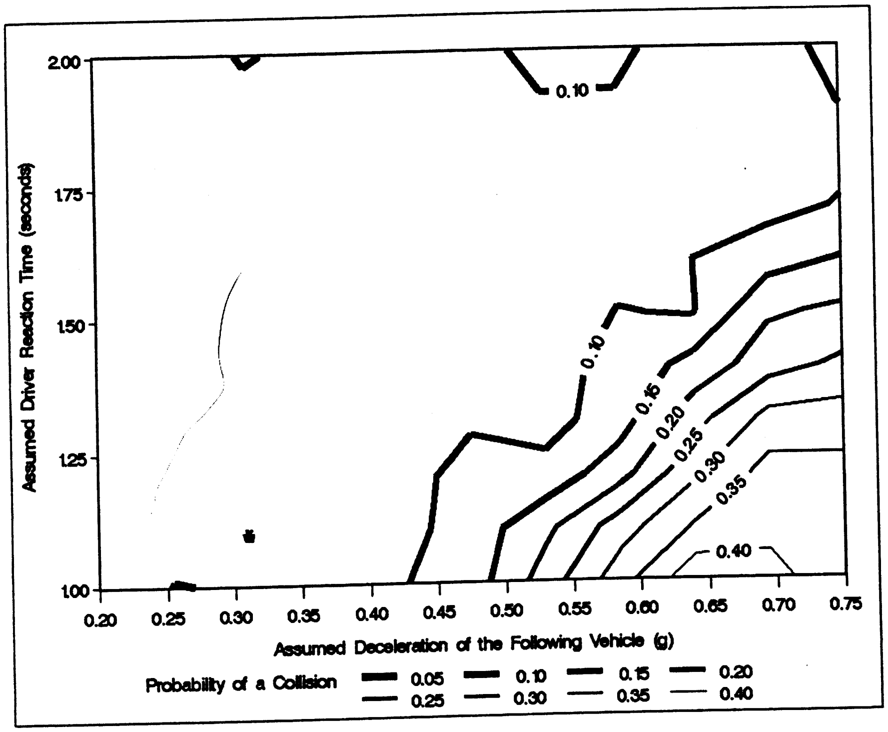

Figure 8. Contour plot of probability of a collision for the algorithm parameter space.

devote additional attention to the roadway, which resulted in a 430 ms faster accelerator release, enabling drivers to avoid a panic-braking situation, to reach the point of maximum braking more gradually, and to stop with a lower mean and maximum deceleration. Thus multiple exposures do not change the fundamental response dynamics but, rather, affect performance by altering how drivers monitor the roadway in the face of distraction. The third criterion concerns the effects of exposure on outcome; the outcome should not change with repeated exposure. The data show that in this experiment, multiple exposures violated this criterion – drivers reacted more quickly and avoided more collisions after the first exposure. Thus the data from the multiple exposures can be interpreted as degrees of distraction, with the first exposure representing a more distracted driver.

Because there were no interaction effects and the dynamics of the driver response did not change, it is theoretically possible to statistically adjust reaction time to the second exposure by 430 ms (i.e., by the amount that driver reaction time decreased from the first to the second exposure). Incorporating these results into a statistical or computational model of driver response could further enhance the information available from a multiple-exposure experiment. Although promising, the results indicate that the second exposure is not equivalent to the first and that data from any multiple-exposure experiment must be carefully examined to ensure that these differences do not jeopardize the validity of the data. As described previously, the results were predicated on a ruse (drivers thought their task was to evaluate simulator validity) that reduced driver expectancies regarding potential collision situations. The nature of the ruse and the specific scenarios used may significantly influence how multiple exposures affect responses to unexpected events.

Future Research

Although this study demonstrated a substantial benefit by warning undistracted drivers in imminent collision situations, several questions remain unanswered. Specifically, although the warning enhanced undistracted drivers' performance in the simulator, warnings might be perceived as a nuisance to undistracted drivers in an actual driving situation. One strategy for reducing nuisance alarms is to integrate the collision warning system with in-vehicle information systems, such that the warning algorithm is more sensitive when the systems are active and the driver is likely to be distracted. Further data collection in operational settings is required to assess driver response to nuisance alarms generated by early warnings and whether or not dynamic adjustment of the algorithm is feasible.

Of more importance, although the study showed no detrimental effects of warning to undistracted drivers, it did not systematically explore how a warning might interfere with an ongoing braking response. Warnings issued when a driver is already responding could interfere with the response process and undermine the benefits of a RECAS. In addition, this study provided drivers with a very limited exposure to the collision warning system. A longer-term study is required to understand the evolution of driver attitudes and to validate the benefits observed in this study.

CONCLUSIONS

For the imminent collision situations examined, drivers dramatically benefited from RECAS warnings. Drivers respond to the collision warning as automation that redirects attention, not as automation that triggers a braking response. By redirecting attention to the road, the RECAS reduced the number and severity of collisions and increased the margin of safety (a larger adjusted minimum TTC). These convergent measures demonstrate the benefit of RECAS warnings. The data show that an early RECAS warning is more beneficial than a late warning; however, drivers who received and complied with a late warning also benefited compared with those who did not receive a warning.

Both distracted and undistracted drivers benefited from the warning. Beyond the direct benefit of avoiding collisions with the lead vehicle, drivers who received the warning decelerated more gradually, which may decrease the risk of being struck from the rear. This could be an important consideration in a comprehensive benefits analysis. The study also showed that RECAS warnings enhance driver response over a wide range of headways, velocities, and lead vehicle decelerations, strongly suggesting that the RECAS algorithm employed in this study can enhance driver response in potential collision situations.

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