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DOT HS 809 448 March 2002

Driver Distraction, Warning Algorithm Parameters, and Driver Response to Imminent Rear-end Collisions in a High-Fidelity Driving Simulator

Technical Report Documentation Page

1. Report No. DOT HS 809 448	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Driver distraction, warning algorithm parameters, and driver response to imminent rear-end collisions in a high-fidelity driving simulator

5. Report Date

March 2002

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s) John D. Lee
Daniel V. McGehee
Timothy L. Brown
Michelle L. Reyes

9. Performing Organization Name and Address

Human Factors & Vehicle Safety Research Program
University of Iowa Public Policy Center
227 South Quad
Iowa City, IA 52242-1192

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
NRD-13
400 Seventh Street, S.W.
Washington, D.C. 20590

13. Type of Report

Technical report

14. Sponsoring Agency Code
NHTSA, NRD-13

15. Supplementary Notes

16. Abstract

This report presents three experiments that use a high-fidelity driving simulator to examine driver response to imminent rear-end-collision situations. The first experiment examines how variations in algorithm parameters affect the ability of a Rear-end Collision Avoidance Systems (RECAS) to aid distracted drivers in avoiding an imminent collision. The results show that an early warning helps drivers to react more quickly and to avoid more collisions than either a late warning or no warning. Compared to no warning, 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 %. These results provide critical data for tradeoff studies of RECAS parameters and nuisance alarm rates. The second experiment examines the ability of the RECAS to help non-distracted drivers avoid an imminent collision. The results show that the RECAS benefits drivers even when they are not distracted. The third study examines the effect of manipulating the urgency of the auditory warning, by changing the volume of the warning tone. Varying the volume levels for the warning tones had no systematic effect on driver response. These studies all show that the RECAS provides a potential safety benefit by reducing the time it takes drivers to remove their foot from the accelerator. The warnings do not speed drivers' application of the brake, increase their maximum deceleration, or affect their mean deceleration.

17. Key Words
Rear-end collisions, Forward Collision Warning, Crash Avoidance, Driver Behavior, Passenger Vehicles

18. Distribution Statement
Document is available to the public from the National Technical Information Service Springfield, VA 22161

19. Security Class.: UNC	20. Security Class.: Unclassified	21. No. of Pages: 61	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

Rear-end collisions account for over 28% of automotive crashes. Because driver inattention is a contributing factor in more than 60% of these collisions, rear-end collision avoidance systems (RECAS) offer a promising approach to reducing crashes, lowering impact speeds, decreasing injuries, and saving lives. This report presents three experiments that use a high-fidelity driving simulator to examine driver response to imminent rear-end-collision situations. The first experiment examines how variations in algorithm parameters affect the ability of a RECAS to aid distracted drivers in avoiding an imminent collision. The results show that an early warning helps drivers to react more quickly and to avoid more collisions than either a late warning or no warning. Compared to no warning, 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 %. These results provide critical data for tradeoff studies of RECAS parameters and nuisance alarm rates. The second experiment examines the ability of the RECAS to help non-distracted drivers avoid an imminent collision. The results show that the RECAS benefits drivers even when they are not distracted. The third study examines the effect of manipulating the urgency of the auditory warning, by changing the volume of the warning tone. Varying the volume levels for the warning tones had no systematic effect on driver response. These studies all show that the RECAS provides a potential safety benefit by reducing the time it takes drivers to remove their foot from the accelerator. The warnings do not speed drivers' application of the brake, increase their maximum deceleration, or affect their mean deceleration.

A cluster analysis shows that drivers who comply with the warnings tend to adopt strategies in which they avoid collisions by braking relatively gradually. This gradual deceleration may decrease the likelihood of the driver being hit from behind. This secondary benefit might be an important consideration in a comprehensive benefits analysis of RECAS. The cluster analysis also suggests some drivers fail to comply with the warnings. If distrust led drivers to ignore the warnings, then nuisance alarms that occur in actual vehicles are likely to increase the number of drivers who discount the warning. Distrust associated with repeated exposure to nuisance alarms could greatly undermine RECAS effectiveness. Understanding why drivers do not always

comply with the warnings may be a critical element in developing an effective collision warning system.

These results have important implications for system evaluation, algorithm design, and driver-vehicle interface design. For system evaluation, the results suggest that repeated exposure to collision situations represents an efficient method for evaluating warning effectiveness. In terms of the design of the warning algorithm, the results suggest that early RECAS warnings are significantly more effective than late warnings, and that they might provide a large safety benefit for drivers who are distracted by in-vehicle technology (e.g., cellular telephones). For the design of the driver-vehicle interface, the results suggest that a simple interface composed of a small icon and an auditory warning can effectively direct drivers' attention to the roadway without inducing a startle response or otherwise impairing driver performance. Increasing the urgency of the warning by increasing its volume did not influence its effectiveness.

These experiments collected data for a limited range of collision situations and algorithm parameters. Addressing general design issues requires extrapolation beyond this limited data set. A theoretically based computational model of driver response to collision warnings was used to extrapolate the current findings to consider a wide range of algorithm parameters. Output from this model identified the combination of parameters most likely to help drivers avoid collisions.

INTRODUCTION

Rear-end collisions account for approximately 28% of all collisions and cause approximately 157 million vehicle-hours of delay annually, accounting for approximately one-third of all crash-caused delay (The National Safety Council, 1996). Driver inattention has been identified as a contributing factor in over 60% of these crashes (Knipling et al., 1993). Compared to driver inattention, environment-related factors have a relatively small effect on the number of rear-end collisions. Specifically, poor visibility was identified as a contributing factor in only 2% of such crashes (Knipling et al., 1993). Because inattention is such a powerful contributor to rear-end collisions, rear-end collision avoidance systems (RECAS) offer a promising approach to mitigating this problem. The promise of increased driving safety through RECAS has generated a substantial body of research (An & Harris, 1996; Hirst & Graham, 1997; Knipling et al., 1993). There are also several RECAS currently under development by Japanese, European, and US automobile manufacturers, in addition to the evaluation efforts sponsored by the National Highway Traffic Safety Administration (NHTSA) (McGehee & Brown, 1998; Tijerina, 1998). The goal of all of these systems is to alert the driver to potential collision situations, return the driver's attention to the roadway, and promote a response that enables the driver to avoid a collision.

The driver interface is an important component of collision avoidance systems. The way in which the warning is presented can greatly influence the speed and appropriateness of drivers' responses. For example, visual displays were found to be more effective in helping drivers maintain their headway than auditory displays (Dingus, McGehee, & Hankey, 1997). More recently, a comparison of auditory, visual, and a combined auditory/visual displays for imminent collision warnings showed that the auditory display led to more responses to valid alerts and fewer responses to false alarms, suggesting that auditory cues may be more appropriate for imminent collision situations (Maltz, Aminov, Abaronov, & Shinar, in press). Similarly, a recent study showed that auditory warnings can effectively guide drivers' collision avoidance response (Belz, Robinson, & Casali, 1999). Substantial research has explored the characteristics of auditory warnings in terms of their ability to promote understanding of warning information. Specifically, perceived urgency has been identified as a critical characteristic of auditory warnings that can promote faster responses (Edworthy, Loxley, & Dennis, 1991; Hellier & Edworthy, 1999; Hellier, Edworthy, & Dennis, 1995). Although perceived urgency has not been examined in the driving domain, warnings that convey high levels of urgency may enhance RECAS effectiveness by promoting shorter reaction times and greater levels of deceleration in response to imminent collision situations.

The warning algorithm determines the timing of the warning and its design is as important as that of the driver interface. A poorly timed warning may actually undermine driver safety (McGehee & Brown, 1998). Several RECAS algorithms have been developed, and the one described by Burgett, Carter, Miller, Najm, and Smith (1998) appears promising. This algorithm generates an alert based on the kinematics of the collision situation. The algorithm triggers a warning at a particular distance between the vehicles (R_W) and a time (t_W) based on the initial distance between the vehicles (R_0), the initial velocity (V_0), and the deceleration of the lead and following vehicles (d_L, d_F). The specific equations for this algorithm depend on initial conditions that define one of three zones. The three zones are defined as: Zone I, the lead vehicle is stopped at the time of the warning; Zone II, the lead vehicle stops before the following vehicle does; and Zone III, the following vehicle stops before the lead vehicle does. Different equations apply for each of the three zones.

Since the equations depend upon the zone, the boundaries separating the zones must be defined. The equations for these boundaries, derived by Burgett et al. (1998), are shown below. These equations define the collision situation and define which equations will be used to calculate the warning onset. Equation 1 defines the boundary between Zones I and II.

$$T_h = \tfrac{1}{2} V_0 \left(\frac{1}{d_L} + \frac{1}{d_F} \right) + \frac{6.67}{V_0} + 1.5 \tag{1}$$

Equation 2 defines the boundary between Zones II and III.

$$T_h = \tfrac{1}{2} V_0 \left(\frac{1}{d_L} - \frac{1}{d_F} \right) + \frac{6.67}{V_0}. \tag{2}$$

For Zone I, equations 3 and 4 define the warning range and range rate.

$$R_W = \frac{V_0^2}{2d_F} + 1.5V_0 + 6.67 \qquad (3)$$

$$\frac{dR_W}{dt} = V_0 \qquad (4)$$

For Zone II, equations 5-7 define the warning range and range-rate.

$$t_W = \frac{1}{2}V_0\left(\frac{1}{d_L} - \frac{1}{d_F}\right) + (T_h - 1.5) - \frac{6.67}{V_0} \qquad (5)$$

$$R_W = R_0 - \frac{1}{2}d_L t_W^2 \qquad (6)$$

$$\frac{dR_W}{dt} = -d_L t_W \qquad (7)$$

For Zone III, the equations for warning range (R_W) and range-rate $\left(\frac{dR_W}{dt}\right)$ remain the same as for Zone II, but the equation for t_W is altered.

$$t_W = \left[\frac{d_F - d_L}{d_F}\right]\left[\frac{2(V_0T_h - 6.67)}{d_L\left(1 - \frac{d_L}{d_F}\right)}\right]^{1/2} - 1.5 \qquad (8)$$

The algorithms associated with each zone identify the warning range and warning time for the initial conditions. An underlying assumption of these algorithms is that in Zones II and III the vehicles are initially traveling at the same speed. The algorithms assume that the deceleration of the vehicles is constant for all zones. In addition, successful collision avoidance in Zone III is predicated upon the ability of the following vehicle to decelerate faster than the lead vehicle (Burgett et al., 1998).

The algorithm has three free parameters: SM (Safety Margin), RT (Reaction Time), and d_F (assumed deceleration of the following vehicle). SM is the distance in feet for the closest point of approach of the two vehicles. RT is the assumed reaction time of the driver of the following vehicle. d_F is the assumed deceleration of the following vehicle. The assumed deceleration follows a step response, rising immediately and remaining constant until the vehicle stops. A computer simulation of this algorithm shows that its performance is highly dependent on the values of its parameters (Brown, Lee, & McGehee, In press). Overestimating drivers' braking response or underestimating drivers' reaction time will lead to algorithm parameters that may not provide the expected safety benefits. The first experiment examines drivers' response to different values of the warning parameter assumed deceleration (d_F) to quantify the effect of this parameter on driver response and algorithm effectiveness.

This research examines how the algorithm and the driver interface affect RECAS effectiveness. One important objective of this research is to investigate the ability of a RECAS to help drivers respond to an imminent collision situation. Two experiments address this general objective. The first experiment examines RECAS effectiveness for distracted drivers, and the second experiment examines whether RECAS can benefit drivers who are not distracted. Another important objective of this research is to understand how the driver interface affects drivers' response to RECAS warnings. The third experiment addresses this by examining the effect of increasing the perceived urgency of the auditory warning. The auditory warning was made more or less urgent by increasing and decreasing its volume (Edworthy & Adams, 1996). To establish the generality of these findings, these issues are examined under 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 process measures of the drivers' response to understand the mechanisms by which RECAS warnings enhance driver performance.

EXPERIMENT 1 METHOD

Purpose

The purpose of the first experiment is to investigate how RECAS warnings affect distracted drivers' response to imminent rear-end collision situations. Specifically, it examines how drivers respond to warnings triggered by different RECAS algorithm parameters under different conditions of speed, headway, and deceleration.

Participants

This experiment included 120 drivers between the ages of 25 and 55. There were an equal number of male and female participants. All were licensed drivers and had normal or corrected to normal vision. They were paid $30 for the time they took to complete the experiment. None of the drivers had participated in a crash avoidance study before.

Apparatus

Data were collected using the Iowa Driving Simulator (IDS). The IDS uses complex computer graphics and four multi-synch projectors to create a highly realistic automobile simulator with a 190-degree forward field-of-view and a 60-degree rear-view. A fully instrumented 1993 Saturn four-door sedan is mounted inside the simulator dome on a six-degree-of-freedom motion base to give drivers motion cues. The vehicle dynamics and the antilock brake system were modeled for a Ford Taurus, a typical mid-sized American car. The Ford Taurus vehicle dynamics model used in this study was developed by NHTSA for use with the National Advanced Driving Simulator (NADS). In addition to the 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. Figure 1 shows the views captured by the four cameras: One camera focused on the throttle and brake pedals; another focused on the driver's face; the third focused on the driver's hands on the steering wheel; and 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.

Figure 1. The multiplexed image of the four camera views that monitored driver behavior.

The RECAS display included an auditory warning and a visual icon. The auditory warning lasted approximately 2.25 s and was composed of four sound bursts, each consisting of four pulses. Each burst was separated by 110 ms and each pulse by approximately 10 ms. The prominent frequency of the pulse was 2,500 Hz. The ambient sound level due to the road and engine noise was 67dBa at 35 mph and 72dBa at 55 mph. The warning tone sound level was 74.8 dBa. The icon was presented 38 inches in front of the driver just above the instrument cluster (6 degrees below the drivers' eye point). Figure 2 shows the icon used in the experiments; it depicted a vehicle colliding with the rear of another vehicle. Both the icon and the warning tone were developed and tested for collision warning (Kiefer et al., 1999; Lerner, 1991).

Figure 2. The icon used to alert drivers to the imminent collision situation.

Experimental design

A five-factor (2^4X3) experimental design, mixed between and within subjects, contrasted the following factors: initial velocity (35 mph rural road and 55 mph freeway); order of initial velocity; first and second exposure to the collision situation; situation severity, composed of lead vehicle deceleration magnitude and the initial headway (two levels); and the warning algorithm, composed of two levels of d_F and a baseline condition (no collision warning device). The warning algorithm and situation severity were introduced as between-subject 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 mph, they would experience another collision situation at 55 mph. The order of presentation was counterbalanced across drivers. The order of the initial velocity, situation severity, and warning algorithm were combined to produce the twelve between subject conditions, each of which included ten drivers, for a total of 120 drivers. Table 1 summarizes the independent variables and Table 2 defines the specific experimental conditions. “Warning time” in Table 2 is defined as the time that elapses between the initial breaking of the lead vehicle and the onset of the warning. “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)	35 mph (56.3 km/h) on a rural highway 55 mph (88.5 km/h) on a freeway
Situation Severity (between)	Low severity, Lead vehicle deceleration 0.40g/Initial headway 1.7 s High severity, Lead vehicle deceleration 0.55g/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 drive Second drive
Order of initial velocity (between)	Low velocity (rural highway) followed by high velocity (freeway) High velocity (freeway) followed by low velocity (rural highway)

Table 2. Experimental conditions for the IDS study of NHTSA warning algorithm parameters.

Condition	Initial velocity (mph)	Lead vehicle deceleration (g)	Initial headway (s)	Algorithm parameter	Warning time (s)	Warning range (ft)	Warning range rate (ft/s)
1	35	0.40	1.70	Baseline, no RECAS			
2	35	0.40	1.70	d_F=0.40 g	0.07	87.2	0.9
3	35	0.40	1.70	d_F=0.75 g	1.00	80.8	12.9
4	35	0.55	2.50	Baseline, no RECAS			
5	35	0.55	2.50	d_F=0.40 g	0.33	127.4	5.8
6	35	0.55	2.50	d_F=0.75 g	1.26	114.4	22.3
7	55	0.40	1.70	Baseline, no RECAS			
8	55	0.40	1.70	d_F=0.40 g	0.12	137.0	1.5
9	55	0.40	1.70	d_F=0.75 g	1.58	121.1	20.3
10	55	0.55	2.50	Baseline, no RECAS			
11	55	0.55	2.50	d_F=0.40 g	0.06	201.6	1.1
12	55	0.55	2.50	d_F=0.75 g	1.52	181.1	27.0

Dependent variables

A range of dependent measures characterizes drivers' response to the collision warnings. Three measures describe the potential safety benefit of the warning and six measures describe how the warning affects drivers' response process.

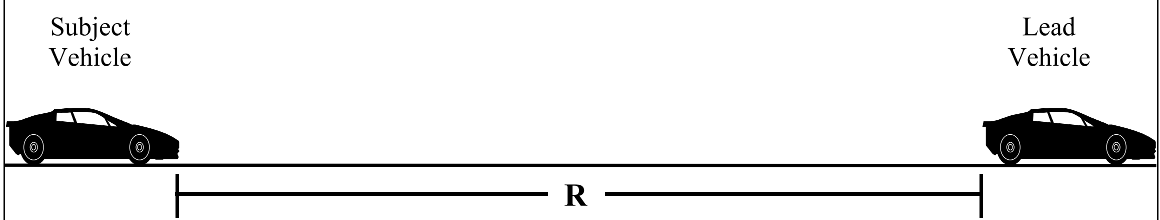
The safety benefit measures quantify the effect of the warnings on collisions or collision potential. The first measure is *collisions*, which specifies whether the driver's vehicle struck the braking lead vehicle. This is a dichotomous measure: a one indicates a collision and a zero indicates that collision 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, the collision velocity is zero. The final safety benefit measure is *adjusted minimum time to collision (TTC)*. Adjusted TTC is a continuous measure of the severity of the collision situation, and is calculated using equations of motion to determine how long it will take the two vehicles to collide at their current relative position, velocity, and deceleration. A positive minimum adjusted TTC represents the safety margin available to the driver. If the vehicles collide, TTC is adjusted by dividing the collision velocity by the deceleration at the point of collision. This produces a negative TTC value that reflects the severity of the collision; a negative minimum adjusted TTC indicates how much sooner the driver needed to begin his/her response to avoid a collision. Figure 3 shows the equations for the adjusted minimum TTC. Adjusted TTC complements the collisions and collision velocity measures by showing the safety benefit for those situations in which drivers avoid collisions and the severity of the collisions when they occur.

$$TTC = \frac{-\dot{R} \pm \sqrt{(\dot{R})^2 - (2\ddot{R})(R)}}{\ddot{R}}$$

$$R = Range$$

$$\dot{R} = \left| LV\_Velocity - SV\_Velocity \right|$$

$$\ddot{R} = \left| LV\_Acceleration - SV\_Acceleration \right|$$



$$TTC = \frac{V_f}{\bar{a}}$$

$$\bar{a} = Acceleration\_of\_SV\_at\_Collision$$

$$V_f = SV\_Velocity\_at\_Collision$$

Figure 3. The adjusted minimum TTC equation measures the safety benefit in collision and non-collision situations.

Several measures of the response process explain how the collision warning influences the safety benefit. These measures reveal what part of the driver's response is affected by the warning. One important description of the response process is the decomposed reaction time, which is made up of three specific measures: accelerator release reaction time, accelerator to brake transition time, and brake to maximum brake transition time. The *accelerator release reaction time* can be measured as 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 in the RECAS conditions. The second component of decomposed reaction time, *accelerator to brake transition time*, specifies how long the driver took to move from releasing the accelerator to beginning to apply the brakes. The third component, *brake to maximum brake transition time*, specifies how long it took the driver to reach maximum deceleration after the initial brake press.

Another important description of the driver's response is the braking profile. The braking profile can be described by the required deceleration, mean deceleration, and maximum deceleration. *Required deceleration* is the constant deceleration required to stop the vehicle safely, given the distance between the vehicles, their relative velocities, and their relative accelerations at the point at which the following vehicle begins to brake. *Mean deceleration* is defined as the average deceleration of the vehicle from first brake press until the driver's vehicle either stops, collides with the lead vehicle, or passes the lead vehicle. *Maximum deceleration* is defined as the peak deceleration between the start and end of the braking event.

Procedure

Upon arriving at the IDS simulation facility, participants completed an informed consent form and were briefed about how to operate the simulator vehicle. 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 instructed to drive normally. They were asked 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 ride-along observer on how to assess the fidelity of the simulator.

The participants began with a five-minute practice drive, in which they were told that the vehicle ahead would brake and that they were to brake to a stop behind it. Following the five-minute practice drive, participants drove two other short road segments, each ending in an imminent collision situation in which the lead vehicle braked suddenly. One drive began and ended on a rural highway, where the drivers encountered a collision situation at an initial velocity of 35 mph. The other drive began on a rural highway, then required drivers to merge onto a freeway, where they encountered the collision situation at an initial velocity of 55 mph.

A secondary task distracted drivers from the roadway. As they drove, a digitized voice periodically asked them to press a button near the rearview mirror. The button initiated a display above the rearview mirror to present a series of one-digit numbers that changed at a rate of four Hz. The driver was asked to watch these numbers and to report how many times the digit "four" appeared. In the imminent collision situation, in addition to initiating the number series the drivers' button press caused the lead vehicle to begin braking. This ensured that drivers were distracted at the precise time the imminent collision situation began to evolve. The task provided a very controlled, although somewhat artificial, exposure to the visual, motor, and cognitive distraction associated with interacting with an in-vehicle information system. It is also very similar to tasks used in other studies of generic in-vehicle distractions (Lamble, Kauranen, Laakso, & Summala, 1999a; Lamble, Laakso, & Summala, 1999b; Summala, Nieminen, & Punto, 1996). To prevent drivers from anticipating collision situations by associating them with the button press, the experiment included several other instances where drivers were asked to perform the secondary task. Likewise, drivers experienced several lead vehicles that did not brake suddenly, and so they were not able to associate a lead vehicle with an imminent collision situation.

The underlying premise of this experiment was that the secondary task replicated the condition of a distracted or inattentive driver at the time the lead vehicle began to brake. To verify this assumption, drivers' glance behavior preceding the collision event was analyzed. Each frame of each videotape for all the collision situations was coded to identify whether the driver was looking at the road, looking at the display, or in transition between the two. Situation severity and initial velocity affect drivers' glance behavior. Higher velocities and shorter headways caused drivers to direct more attention to the road. 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% compared to 35.6%, $F(1,106)=8.51$, $p<0.01$. Drivers also glanced away from the road fewer times, 1.06 compared to 1.35 times, $F(1,106)=14.53$, $p<0.001$. These data show that the secondary task did draw 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 drove realistically by dividing their attention between the road and the in-vehicle task. Drivers adapted their behavior and reduced the attention they were willing to devote to the secondary task after the initial collision situation.

Before each imminent collision situation, the simulator "coupled" the participants' vehicle to the lead vehicle at a fixed headway. At the time the button was pushed, the vehicles were precisely separated by the time headway specified in the experimental design. When the drivers pushed the button, the lead vehicle began to brake at a constant deceleration, coming to an abrupt stop.

To limit responses to the collision situation to braking, conditions were devised to discourage steering as a response to the threat. 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. While steering could be an appropriate response to the warning, an important objective of this experiment was to evaluate the warning algorithm in the worse case condition when only braking is possible. Therefore, drivers were constrained to only braking to avoid colliding with the lead vehicle.

EXPERIMENT 1 RESULTS

The data from each driver were combined to form a database containing 240 imminent collision situations. Some data elements were missing for four braking events. 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 of the warning. For these drivers, it was possible to identify the time at which 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 mixed linear model (MIXED) procedure of SAS. The dependent variables associated with the potential safety benefit of the RECAS are described first, followed by a description of the variables associated with the underlying response process.

Potential safety benefit of the RECAS

Figure 4 shows that the percent of imminent collision situations that ended in a collision, the collision velocity, and the adjusted minimum TTC all provide convergent evidence regarding the safety benefit of the RECAS. The warning reduced the percent of collisions, $F(2,108)=16.07$ $p<0.0001$). The early warning provided the greatest benefit, reducing the rate of collisions to 8.8%, whereas the late warning reduced the rate of collisions to 22.5%, compared to 45.5% in the baseline condition. Similarly, the warning reduced collision velocity, $F(2,108)=15.51$ $p<0.0001$. The collision velocity without the warning (4.74 m/s) was greater than that with the late warning (1.68 m/s) or the early warning (0.88 m/s). The difference in collision velocity between the two warning conditions was not statistically significant $t(108)= 1.08$ $p = 0.2808$. The minimum TTC shows a benefit for the warning, with the early warning (2.79 s) providing a greater safety margin than the late warning (0.90 s), compared to the baseline of (0.09 s), $F(2,108)=32.62$ $p<0.0001$. Figure 4 shows the results of the post hoc comparisons; the letters A, B, C indicate that conditions are significantly different.

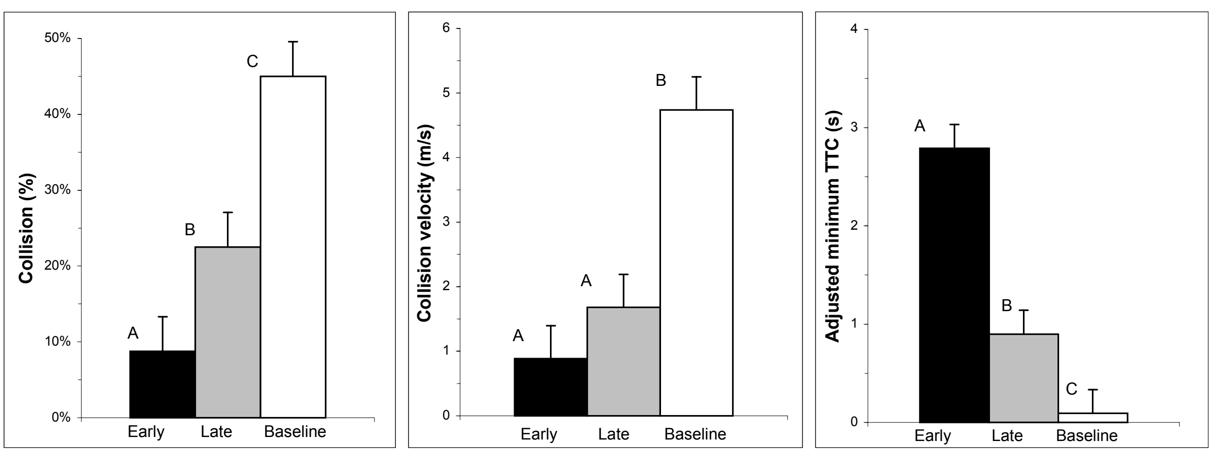


Figure 4. Safety benefit of early RECAS warning compared to the late warning and the baseline condition without a warning.

Besides the effect of the warning, the severity of the collision situation and previous exposure to a collision situation had 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 low severity situations (1.70 s headway, 0.40 g deceleration) (30.4%, 20.4%), $F(1,108)= 4.03$ $p<0.05$; to higher collision velocities (3.2 m/s, 1.6 m/s), $F(1,108)= 8.36$ $p<0.005$; and to smaller minimum adjusted time to collision values (0.87 s, 1.65 s), $F(1,108)= 7.96$ $p<0.01$. Similarly, as expected, the first exposure led to more collisions than the second exposure (38.3%, 12.5%), $F(1,108)= 29.4$ $p<0.0001$; as well as to higher collision velocities (3.6 m/s, 1.3 m/s), $F(1,108)= 19.33$ $p<0.0001$; and to smaller minimum adjusted time to collision values (0.62 s, 1.90 s), $F(1,108)= 35.9$ $p<0.0001$. Interactions between the RECAS parameters, initial velocity, situation severity, order, and exposure did not reach statistical significance.

Response process: Reaction time and braking profile

By decomposing the drivers' reaction time and examining the drivers' braking profile it is possible to show how the RECAS generates the observed safety benefit. The drivers' reaction time is composed of three time periods: onset of lead vehicle braking to the accelerator release, movement time from accelerator release to initial brake press, and initial brake press to maximum deceleration. The RECAS could generate the observed benefits by reducing the duration of any one of these components, by reducing the required deceleration, or by increasing drivers' mean or maximum deceleration.

Figure 5 shows the effect of the RECAS warning on drivers' response process. Table 2 shows that the mean onset for the early warning was 0.145 s, and the mean onset of the late warning was 1.34 s. Not surprisingly, this difference was reflected in drivers' reaction time. The timing of the warning influenced how quickly drivers released the accelerator in response to the braking of the lead vehicle, $F(2,108)=47.4$, $p<0.0001$. The early warning led drivers to react more quickly (1.35 s) than the late warning (2.10 s) or the baseline condition (2.21 s). The difference between the baseline and late warning failed to reach statistical significance. However, drivers released the accelerator more quickly in response to the late warning (0.76 s) compared to the early warning (1.14 s), $F(2,72)=23.38$, $p<0.0001$. These results suggest that in the late warning condition, some drivers may recognize the collision threat and begin responding before the warning is triggered. The warning had no statistically reliable effect on the movement time from the accelerator to initial brake press, $F(2,108)=0.23$. Interestingly, the warning is associated with an *increased* time from the initial brake press to maximum brake pressure, $F(2,108)=9.6$, $p<0.0001$. Drivers in the baseline condition moved from initial brake press to maximum braking more quickly (1.42 s) than drivers with either the late warning (1.74 s) or the early warning (1.91 s). The effect of the warning did not reach statistical significance for required deceleration, $F(2,108)=2.94$, $p>0.05$, mean deceleration, $F(2,108)=3.06$, $p>0.05$, or maximum deceleration, $F(2,108)=0.93$, $p>0.05$.

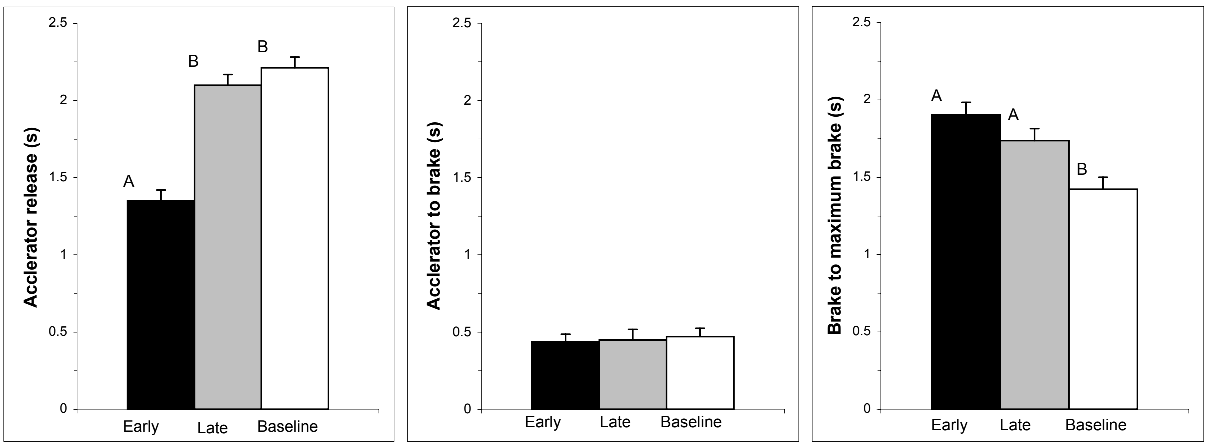


Figure 5. The effect of RECAS warnings on the response process.

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 s, 1.67 s), $F(1,108)=39.52$, $p<0.0001$. Reaction to the warning was also faster during the second exposure (1.16 s, 0.74 s), $F(2,72)=43.71$, $p<0.0001$. As with the early warning, the time from initial brake application to maximum braking increased slightly with the second exposure (1.61 s, 1.77 s), $F(1,108)=5.15$, $p<0.05$. Similarly, both the mean and maximum deceleration were slightly lower during the second exposure, $F(1,108)=8.7$, $p<0.01$, $F(1,108)=9.58$, $p<0.01$ The mean and maximum deceleration were 0.60 g and 0.84 g for the first exposure, and 0.56 g and 0.81 g for the second exposure. Although statistically significant, the size of these effects is not practically meaningful. Interestingly, the required deceleration was not affected by exposure, $F(1,108)=0.01$, $p>0.05$.

The severity of the situation also influenced drivers' response. The high-severity situation (2.50 s headway, 0.55 g) led to a longer mean accelerator release time—2.04 s, compared to 1.73 s for the low-severity situation (1.70 s headway, 0.40 g deceleration), $F(1,108)=15.91$, $p<0.0001$. This parallels the effect of situation severity on collisions and collision severity; the more severe collision situation led to more collisions. Based on the data in Table 2, if drivers were to respond in a manner that exactly mimicked 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. These response times are based on the mean warning time plus a 1.0 s reaction time. The 100 ms difference in the expected accelerator release time compares to the observed 310 ms difference, indicating that drivers reacted more slowly than was required by the more severe collision situation. Drivers compensated for this longer accelerator release time with a higher mean deceleration. The more severe situation led to a higher mean deceleration (0.60 g) compared to the less severe situation (0.55 g), $F(1,108)=8.04$, $p<0.01$. Similarly, the more severe situation led to a higher required deceleration (0.55 g) compared to the less severe situation (0.43 g), $F(1,108)=312.8$, $p<0.0001$.

The initial velocity of the vehicles had a large effect on how drivers responded, although it did not have a statistically significant effect on the number of collisions. High initial velocity was associated with high required deceleration (0.51g) compared to the relatively low required deceleration (0.47 g) seen in the low-velocity condition, $F(1,108)=19.82$, $p<0.0001$. Figure 6 summarizes the effect of initial velocity on the response process. Initial velocity had a marginal effect on initial accelerator release time ($F(1,108)=3.64$, $p=0.059$), but a strong effect on the time drivers took to move from the accelerator to the brake, $F(1,108)=15.74$, $p<0.0001$. The main effect of the accelerator to brake movement time interacts with the presence of the RECAS, $F(1,108)=3.42$, $p<0.05$, so that movement time was most influenced by initial velocity when drivers did not have the RECAS. The movement time was shorter for the low initial velocity (310 ms) than it was for the higher initial velocity (630 ms) during the baseline condition. When the RECAS was present, the difference in movement time was even less (390 ms for low initial velocity and 480 ms for high initial velocity). Initial velocity also affected the time between initial brake press and maximum deceleration, $F(1,108)=83.86$, $p<0.0001$. For the high-initial-velocity condition, drivers moved from initial brake press to maximum deceleration in 2.01 s; for the low-initial-velocity condition, they took only 1.36 s. The data in Table 2 show that if drivers were to respond in a manner that exactly mimicked the constraints embodied in the algorithms (the mean warning time plus a 1.0 s reaction time), they would release the accelerator and begin braking in 1.82 s for the high-initial-velocity condition, and in 1.66 s for the low-initial-velocity condition. Drivers released the accelerator slightly later than algorithm would predict, but they compensated with a faster accelerator to brake movement, and depressed the brake more quickly.

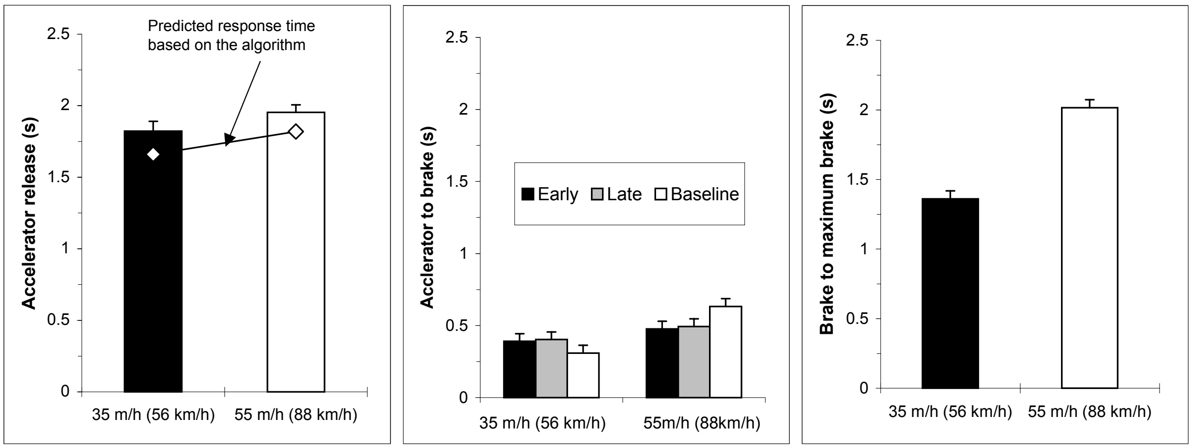


Figure 6. Drivers are 100 ms slower to respond to the braking lead vehicle when the initial velocity is lower, but they compensate by moving to the brake and depressing the brake more quickly.

Clusters of similar response patterns

The analyses of the safety benefit and the response process show the benefits of the RECAS, and how it achieves those benefits by affecting the way drivers respond to collision situations. However, the analyses do not provide a holistic view of how the variables jointly characterize different ways of responding to imminent collision situations. Exploring the data with a cluster analysis provides the missing holistic perspective and reveals six patterns of collision outcomes and driver response.

Table 3 shows the percent of collisions, the reaction times, and the braking profiles for each of the six clusters. The clusters were identified using k-means cluster analysis with SPSS. Each of the 236 events was assigned to one of the six clusters. Combinations of initial reaction time and maximum deceleration that maximize the difference in the adjusted time to collision define the cluster centers. The clusters in Table 3 are ordered by the adjusted minimum time to collision.

Table 3 shows the decomposed reaction time and braking profile measures that describe the underlying behaviors influencing collisions. The collision probability of the six clusters differs dramatically, ranging from Cluster 1 with no collisions to Cluster 6 with an 85% collision rate. The negative TTC and relatively high collision velocity for the events in Cluster 6 indicate the severity of these collisions. Clusters 1–3 represent responses that generally avoid collisions, whereas Clusters 4-6 represent relatively ineffective response strategies. Interestingly, the mean deceleration is lower (0.54 g) for those clusters in which collisions were generally avoided (Clusters 1–3), and the mean deceleration is higher for those clusters in which collisions were more likely to occur (0.64 g). This difference in mean deceleration points to a potential indirect benefit of the warning. Beyond the direct benefit of avoiding rear-end collisions, drivers who received the early warning tended to decelerate more gradually. This works to decrease the risk of being struck from the rear associated with the abrupt deceleration of drivers who do not receive a warning or receive a late warning.

Table 3 shows that the first three clusters can be termed “Successful” and the last three “Unsuccessful.” By examining the response pattern of the clusters in these two groups it is possible to see how different response strategies and collision scenarios can lead to successful or unsuccessful outcomes.

Each of the six clusters has been labeled according to the response pattern it represents. In Cluster 1, drivers released the accelerator early (1.12 s), followed by a slow movement to the brake (0.63 s) and a slow depression of the brake (2.83 s). Thus, Cluster 1 can be characterized as an “Early & 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 a very fast depression of the brake (0.83 s). Based on these characteristics, Cluster 6 can be termed “Very late & Very fast.” The very rapid accelerator-to-brake movement time in Cluster 6 may reflect drivers’ attempt to compensate for a late initial response. Each of the six clusters summarized in Table 3 represents a substantially different response strategy in terms of response process and event outcome. These strategies may reflect either the driving scenario or drivers’ particular response tendencies and cognitive state. Understanding the underlying response process and the conditions that promote successful strategies could help guide RECAS design.

Table 3. Clusters and their characteristics that describe drivers response to imminent collision situations.

Successful Clusters	1 Early & Slow	2 Early & Fast	3 Moderate & Fast
Minimum TTC (s)	3.33	2.87	1.42
% Collisions	0%	3%	11%
Collision velocity (m/s)	-	-	5.8
Accelerator release (s)	1.12	1.20	1.69
Accelerator to brake (s)	0.63	0.50	0.42
Brake to maximum decel. (s)	2.83	1.66	1.06
Mean deceleration (g)	0.56	0.54	0.53
Maximum deceleration (g)	0.83	0.82	0.79
Total events	26	61	38

Unsuccessful Clusters	4 Late & Slow	5 Late & Fast	6 Very Late & Very Fast
Minimum TTC (s)	0.90	0.38	-1.84
% Collisions	22%	39%	85%
Collision velocity (m/s)	5.4	7.7	12.1
Accelerator release (s)	2.30	2.28	3.00
Accelerator to brake (s)	0.41	0.43	0.31
Brake to maximum decel. (s)	2.82	1.71	0.83
Mean deceleration (g)	0.64	0.65	0.61
Maximum deceleration (g)	0.87	0.87	0.81
Total events	23	54	34

Analysis of the membership of the six clusters reveals that the experimental conditions influenced drivers' response strategies. As expected, the warning strongly influenced response strategies, $\chi^2(10) = 101.53$, $p<0.0001$. Figure 7 shows this effect, with Clusters 1 and 2 reflecting compliance with the early warning, and Clusters 3 and 4 reflecting compliance with the late warning. Additionally, for drivers in the baseline condition, Clusters 2 and 3 reflect behavior consistent with the kinematic constraints embodied in the warning algorithms. Clusters 5 and 6 represent situations where drivers failed to respond effectively to either the warnings or the perceptual cues that indicate a potential collision situation. Interestingly, although Cluster 5 represents unsuccessful collision avoidance it is composed primarily of drivers who received the late warning.

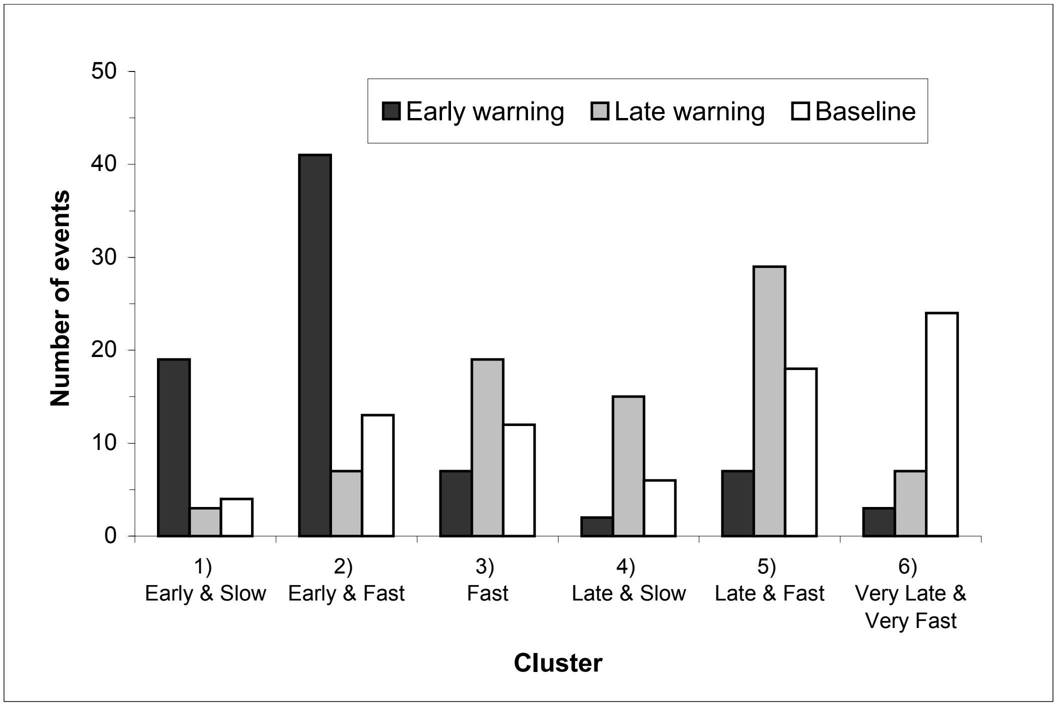


Figure 7. The effect of the timing and presence of the warnings on the drivers' response strategies.

Drivers' response to high- and low-initial-velocity conditions confirms the effect of the warnings on drivers' strategies. The initial velocity, combined with the headway and deceleration of the lead vehicle, determines when the algorithm will trigger the alert, as shown in Table 2. Interestingly, the severity of the collision situation did not have a statistically significant effect on the response strategy adopted by drivers, $\chi^2(5) = 10.35$, $p > 0.05$. The strategies drivers adopted were, however, highly dependent on the initial velocity, $\chi^2(5) = 68.35$ $p < 0.0001$. Specifically, the second column of Table 4 shows that Cluster 1 is composed almost entirely of the high-initial-velocity conditions, reflecting the early-warning onset (0.09 s) for the combination of early-warning and high-initial-velocity conditions. This compares to the later warning onset for the combination of early-warning (0.20 s) and low-initial-velocity conditions, which is reflected in the high proportion of these cases in Cluster 2. The early accelerator release in Clusters 1 and 2 strongly reflects the benefit of the early warning. A similar pattern exists for Clusters 3 and 4. The relatively early accelerator release in Cluster 3 corresponds to the warning onset of 1.13 s for the combination of late-warning and low–initial-velocity conditions. This compares to 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 the high-initial-velocity conditions. Cluster 3 is primarily composed of drivers in the low-initial-velocity condition, and Cluster 4 is entirely composed of drivers in the high-initial-velocity condition. This pattern holds for those drivers who received a warning and for many of those who did not. Of the 61 events in Clusters 3 and 4, 18 represent the baseline condition where a warning was not given. This suggests some drivers were sensitive to the kinematic constraints in the absence of 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

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 Table 4 there are approximately the same number of events for the late-warning in the high-initial-velocity condition (14) as there are for the low-initial-velocity condition (15). The same holds true for the early-warning and baseline conditions. This contrasts with Cluster 3, which contains 17 late-warning cases in the low–initial-velocity condition and only 2 in the high-initial-velocity condition, and with Cluster 4, which contains no late-warning cases in the low-initial-velocity condition and 15 in the high-initial-velocity condition. The experimental conditions of severity and velocity did not have a statistically significant effect on cluster membership in Clusters 5 and

6, $\chi^2(1) = 0.05$, $p > 0.05$ and $\chi^2(1) = 0.20$, $p > 0.05$. Interestingly, drivers received a warning in more than half of 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 show drivers who did not comply with the warning.

If drivers in Clusters 5 and 6 did in fact ignore the warnings and were not attuned to the kinematic constraints of the situation, then it is likely that fewer drivers would be included in these clusters in their second exposure to the collision situation. Prior exposure and experience with the reliable RECAS should prompt more effective collision avoidance strategies. Figure 8 shows that this was the case, and that the cluster memberships shifted as drivers became more experienced with the RECAS and the experiment, $\chi^2(5) = 18.14$, $p < 0.005$. The number of cases in these two clusters dropped 48.3% after drivers were exposed to the first collision event.

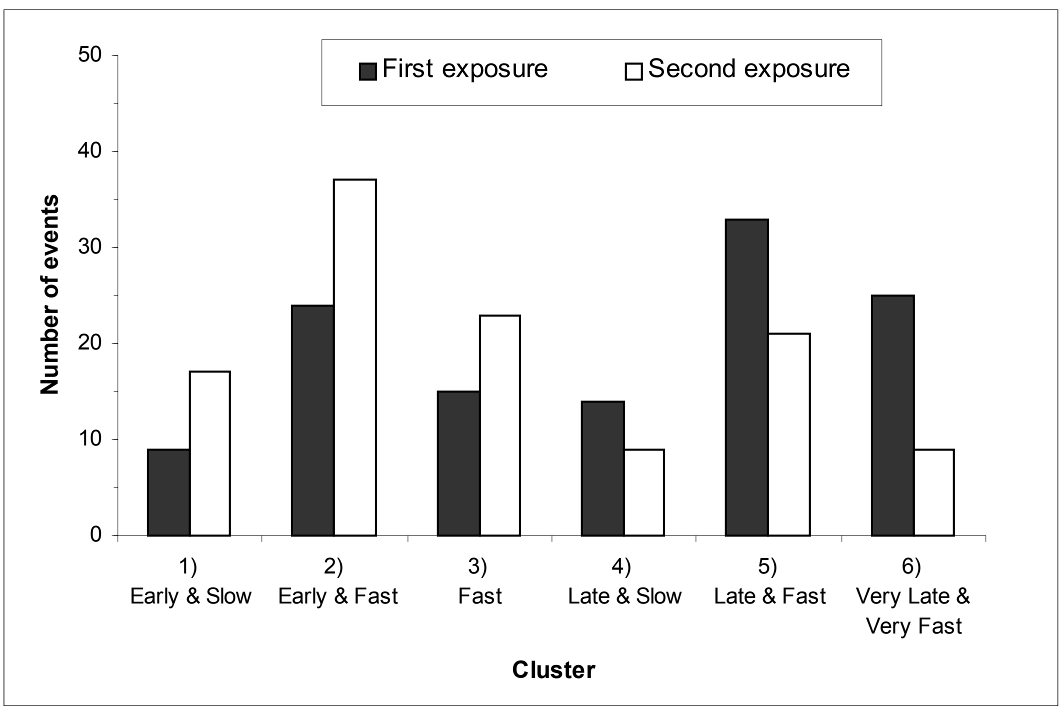


Figure 8. The effect of exposure to the collision event on drivers' response strategies.

EXPERIMENT 1 DISCUSSION

The objective of this experiment was to investigate the effect of RECAS algorithms on drivers' response to imminent collision situations. The results address several aspects of this objective. First, the data show that RECAS warnings—particularly early warnings—provide a substantial benefit to drivers. Compared to no warning, 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 the warning affects drivers' response process. RECAS helps drivers avoid collisions by speeding their accelerator release; it does not enhance any other aspect of the response. Drivers do not depress the brake more quickly or brake 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.

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 other two clusters reflect the behavior of drivers who were not attuned to the warnings and the driving environment. Although many of these drivers did not receive a warning, some of them who did receive a warning failed to respond appropriately. This indicates that although a warning may help drivers choose an appropriate avoidance strategy and thus prevent collisions, the warning does not guarantee the driver will choose an appropriate strategy. It is surprising that some drivers seemed to ignore or discount the warning, given that the warnings always accurately indicated a collision situation. One explanation is that some drivers did not fully understand the nature and purpose of the warning. Another explanation is that some drivers did not trust the warning and so discounted it (Lee & Moray, 1994). If distrust led drivers to ignore the warnings, then nuisance and false alarms that are prone to 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 greatly undermine RECAS effectiveness. Understanding the cause of poor compliance may be a critical element in developing an effective collision warning system.

Although the algorithm did not enhance any aspect of the response other than the initial accelerator release, drivers' responses were sensitive to the initial velocity and severity of the collision situation. For example, the movement time from the accelerator to the brake was very sensitive to the initial velocity. At lower velocities, drivers seemed to misestimate the need to brake due to the long distance between the vehicles. 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 response to these conditions shows that drivers modulate their response according to the evolving situation, and that braking is not an open-loop process. These results have important implications for modeling driver behavior to enhance RECAS design and to estimate its benefits. By understanding how RECAS enhances drivers' collision avoidance behavior, more accurate computer models can be developed to identify appropriate RECAS parameters. These models can evaluate a wide range of algorithm parameters that would not be feasible with simulator, on-road, or test track experiments.

Although this experiment provides important insights into the potential benefits of RECAS warnings, it leaves several issues unresolved. This study provided drivers with a very limited exposure to the RECAS. Drivers experienced only three warnings over 30 minutes. This raises questions regarding whether drivers' responses would improve with increased exposure, and whether an imperfect system that generates occasional nuisance alarms would undermine drivers' compliance with the warnings. A second issue that this experiment did not address is what benefit if any RECAS might provide to drivers who are not distracted. Undistracted drivers who receive a warning might not benefit from the warning and might even suffer a disadvantage if the warning distracted them from responding to the lead vehicle. The effect of warnings on the response of non-distracted drivers is a particularly critical issue from the perspective of estimating the benefits of RECAS. Experiment 2 addresses this issue.

EXPERIMENT 2 METHOD

Purpose

The objective of this experiment is to investigate how drivers might respond to imminent collision situations when they are not distracted at the beginning of the collision situation.

Participants

Data were collected from 20 additional drivers between the ages of 25 and 55. Inclusion criteria were the same as in Experiment 1.

Apparatus

The apparatus was the same as in Experiment 1.

Experimental design

Experiment 2 focused on a subset of the experimental conditions in Experiment 1. Specifically, only the low severity and early warning conditions were examined. These conditions were chosen because they had the lowest variance in Experiment 1, and so could be expected to provide the most sensitive statistical comparisons. The data from non-distracted drivers were compared to data gathered under the same conditions in Experiment 1. Table 5 shows the experimental conditions considered in Experiment 2. Ten drivers were included in the baseline condition without distraction and ten drivers in the early warning condition without distraction. Data for 20 distracted drivers in the baseline and early warning conditions from Experiment 1 were used for comparison.

Dependent variables

The dependent variables were the same as in Experiment 1.

Table 5. Experimental conditions to examine the influence of driver distraction on the benefit of the RECAS.

Condition	Initial velocity (mph)	Lead vehicle deceleration (g)	Initial headway (s)	Algorithm parameter	Distracted by secondary task
1	35	0.40	1.70	Baseline, no RECAS	Yes (Exp. 1 data)
2	35	0.40	1.70	d_F=0.40 g	Yes (Exp. 1 data)
3	55	0.40	1.70	Baseline, no RECAS	Yes (Exp. 1 data)
4	55	0.40	1.70	d_F=0.40 g	Yes (Exp. 1 data)
5	35	0.40	1.70	Baseline, no RECAS	No
6	35	0.40	1.70	d_F=0.40 g	No
7	55	0.40	1.70	Baseline, no RECAS	No
8	55	0.40	1.70	d_F=0.40 g	No

Procedure

The experimental protocol was identical to that used in Experiment 1 except that the secondary task was eliminated.

EXPERIMENT 2 RESULTS

The data from all drivers were combined to form a database containing 80 imminent collision situations. Some data elements were missing for three cases. This was caused by situations in which, for example, a 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 mixed linear model (MIXED) procedure of SAS. The dependent variables associated with the potential safety benefit of the RECAS are described first, followed by a description of the variables associated with the underlying response process.

Safety benefit of the RECAS

The percentage of imminent collision situations that end in a collision, the collision velocity, and minimum adjusted TTC all indicate that RECAS provides a safety benefit to both distracted and undistracted drivers. The warning reduced the percentage of collisions, $F(1,52)=20.17$, $p<0.001$. With an early warning, drivers collided in only 1.4% of collision situations, compared to 26.0%

in the baseline condition. This effect depends on driver distraction, with drivers who received a warning avoiding most collisions whether they had been distracted or not, $F(1,52)=4.95$, $p<0.05$. Figure 9 shows that undistracted drivers collided 14.2% of the time without a warning and 0.7% of the time when a warning was given; distracted drivers, on the other hand, collided 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 than undistracted drivers, $F(1,52)=6.34$, $p<0.05$. Distracted drivers were involved in collisions 20.0% of the time compared to 7.4% for undistracted drivers. The warning also reduced the collision velocity, $F(1,52)=11.36$, $p<0.01$. Without a warning, drivers collided at 2.1 m/s compared to 0.1 m/s for drivers who received a warning. The warning also increased the minimum adjusted TTC, $F(1,52)=38.40$, $p<0.001$. Drivers without a warning had a minimum adjusted TTC of 1.0 seconds compared to 3.5 seconds for drivers who received a warning. For both collision velocity and adjusted minimum TTC, the interaction between distraction and the warning did not reach statistical significance. This suggests that a RECAS warning benefits undistracted and distracted drivers equally. The data provide no evidence to suggest that warning undistracted drivers degrades driving safety.

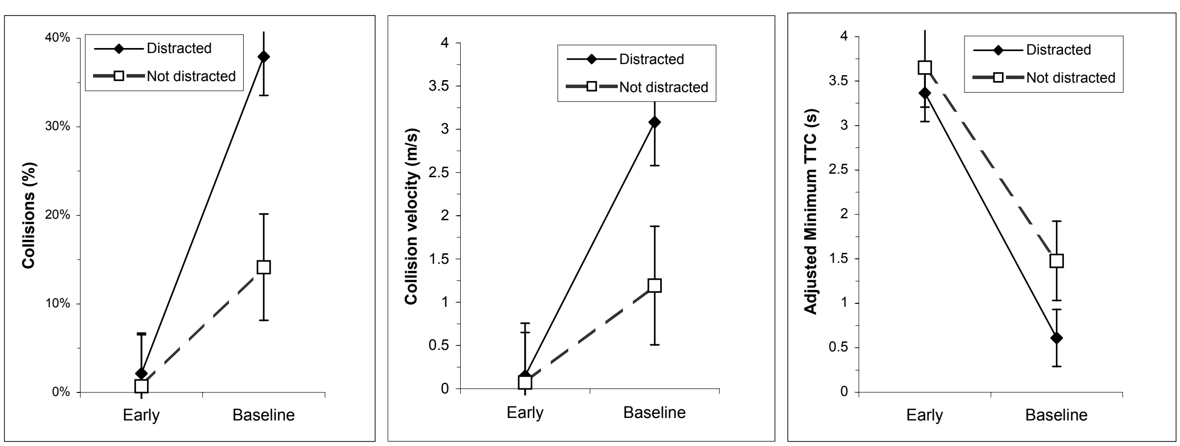


Figure 9. The effect of RECAS warning and distraction on safety.

In addition to the effect of RECAS warnings and driver distraction, several other interesting effects were found. As in Experiment 1, the percentage of imminent collision situations that ended in a collision, the collision velocity, and minimum adjusted TTC show that performance improved after the first exposure to the collision situation. Drivers were less likely to collide on their second exposure, $F(1,52)=16.43$, $p<0.001$. Specifically, drivers collided in 24.6% of the first collision situations, compared to 2.9% of the second. Drivers also had lower collision velocities on their second exposure, $F(1,52)=11.89$, $p<0.01$. During the first exposure, the collision velocity was 1.9 m/s compared to 0.3 m/s during the second. The minimum adjusted TTC was also larger for the second exposure than for the first, $F(1,52)=15.59$, $p<0.01$. Drivers' safety margin increased from an adjusted TTC of 1.7 s to 2.9 s after the first exposure.

The effect of exposure on the percentage of collisions is complicated by an interaction with the RECAS warning for percentage of collisions, $F(1,52)=11.76$, $p<0.01$, and collision velocity, $F(1,52)=8.47$, $p<0.01$. When no warning was given, drivers collided 46.0% of the time with a collision velocity of 3.6 m/s in the first exposure, and 6.0% of the time with a collision velocity of 0.7 m/s in the second exposure. When a warning was given, drivers collided 3.1% of the time with a collision velocity of 0.2 m/s in the first exposure, and did not experience any collisions in the second exposure. This interaction reflects a floor effect: there was less room for improvement from first to second exposure for the early warning group compared to the baseline. The order in which drivers experienced the high- and low-velocity collision situations affected their overall chance of colliding. Drivers who were exposed to the high-initial-velocity situation first experienced more collisions (19.3%) than drivers who experienced the low-initial-velocity condition first (8.2%), $F(1,52)=4.08$, $p<0.05$. Experiencing the high-velocity collision situation first, however, seems to better prepare drivers for the second exposure.

Response process: Reaction time and braking profile

RECAS warnings and driver distraction also affected drivers' response to the collision situation. Figure 10 shows the effect of distraction and the RECAS warning on drivers' reaction time. The warning increased the speed of the accelerator release, $F(1,52)=64.22$, $p<0.0001$. Drivers who received a warning released the accelerator in only 1.03 s, compared to drivers in the baseline condition who took 1.73 s to release the accelerator. This reduced reaction time was reflected in the lower required deceleration at the point of brake application—0.41g for those with the warning and 0.44 for those without, $F(1,52)=83.85$, $p<0.0001$. Distracted drivers released the accelerator later in response to both the lead vehicle braking, $F(1,52)=24.36$, $p<0.0001$, and to the warning onset, $F(1,26)=5.82$, $p<0.05$. Distracted drivers took 1.59 s to respond to the lead vehicle and 1.04 s to respond to the warning, whereas undistracted drivers took only 1.16 s to respond to the lead vehicle and only 0.76 s to respond to the warning. The effect of distraction on required deceleration was also evident, with distracted drivers having a higher required deceleration (0.43g) than undistracted drivers (0.41g), $F(1,52)=21.42$, $p<0.0001$. As shown in Figure 10, neither the warning nor driver distraction had any effect on transition time from accelerator to brake. The warning did increase the time between initial brake press and maximum deceleration, however, $F(1,26)=5.54$, $p<0.05$. With the warning, drivers moved from initial brake application to maximum brake application in 1.95 s compared to 1.62 s when they did not receive the warning. Distracted drivers, on the other hand, depressed the brake faster than undistracted drivers, $F(1,52)=5.71$, $p<0.05$. Distracted drivers transitioned from brake press to maximum brake in 1.62 s, whereas undistracted drivers made the transition in 1.95 s. The warning did not interact with driver distraction for any element of the response process, suggesting that, like the safety benefit, the warning enhances the driver's response independently of whether the driver is distracted or not.

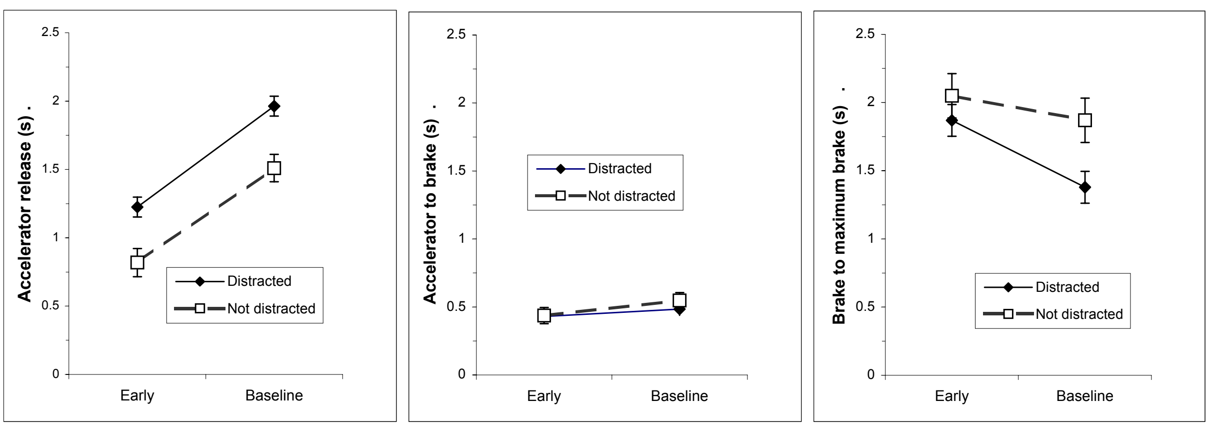


Figure 10. The effect of distraction and RECAS warnings on the response process.

The warning interacted with initial velocity to influence the transition time between the accelerator and the brake, $F(1,52)=9.25$, $p<0.01$. Initial velocity affected drivers' transition from the accelerator to the brake only in the baseline condition. When drivers had 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 time was nearly equal—0.44 s for the high and 0.42 s for the low initial velocity. Interestingly, there was no interaction between the warning and distraction for accelerator release, $F(1,52)=0.05$, p=0.824, or for the transition from brake to maximum brake, $F(1,52)=1.22$, p=0.274.

In addition to RECAS warnings and driver distraction, exposure, initial velocity, and order affected drivers' responses. The second exposure to the collision situation reduced drivers' reaction time to both the event, $F(1,52)=10.36$, $p<0.005$, and the warning, $F(1,26)=9.99$, $p<0.005$. 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 to 1.22 s and 0.75 s for the second exposure. Higher initial velocity led to a longer accelerator-to-brake transition time, $F(1,52)=10.91$, $p<0.001$. For the lower initial velocity, drivers took 0.39 s to transition from the accelerator to the brake, whereas for the high initial velocity drivers took 0.56 s. Similarly, the initial velocity also affected the time to transition from initial brake application to maximum deceleration, $F(1,52)=25.80$, $p<0.0001$. For the lower initial velocity, drivers took 1.51 s to transition from brake to maximum brake, whereas for the high initial velocity, drivers took 2.08 s. The accelerator-to-brake transition time was affected by the order in which drivers were exposed to the high- and low-initial-velocity conditions, $F(1,52)=5.31$, $p<0.05$. Drivers who started with the high-velocity condition had a mean transition time of 0.54 s, whereas drivers who started with the low-velocity condition had a mean transition time of 0.41 s. Taken together these results suggest that drivers' initial perception of the collision situation is moderated by the warning, but their response process is moderated by the perceptual cues. In the high-velocity condition, the lead vehicle is further away and the perceptual cues are not as salient; as a result, braking is slightly delayed. This is confirmed by the effect of initial velocity on the required deceleration at the point of brake application. Drivers in the high-initial-velocity conditions have a required deceleration of 0.42g, and drivers in the low-velocity conditions have a required deceleration of 0.41g, $F(1,52)=4.49$, $p<0.05$.

In addition to the changes associated with response timing, there were a number of effects relating to the deceleration profile. There were no significant main effects for either distraction or condition for either mean deceleration or maximum deceleration; however, deceleration did depend on an interaction between distraction and order of trials, $F(1,52)=8.98$, $p<0.01$, and was further complicated by a three-way interaction with condition, $F(1,52)=6.30$, $p<0.05$. For baseline conditions, the effect of distraction depended on the order of the trials, with order 1 (low then high velocity) leading to a high deceleration when drivers were not distracted, and order 2 (high then low velocity) leading to a high deceleration when drivers were distracted. In addition to this complex interaction, maximum deceleration also depended on an interaction between distraction and order of trials $F(1,52)=5.63$, $p<0.05$.

Deceleration was also affected by the initial velocity type and by exposure. For the lower initial velocity, drivers used greater average deceleration, $F(1,52)=6.64$, $p<0.05$, and greater maximum deceleration, $F(1,52)=6.34$, $p<0.05$. On the rural road, drivers decelerated at 0.55 g and had a maximum deceleration of 0.81 g, whereas, for the high initial velocity, drivers decelerated at 0.49 g and had a maximum deceleration of 0.77 g. Maximum deceleration was also influenced by exposure, $F(1,52)=4.10$, $p<0.05$. On the first exposure, drivers' maximum deceleration was 0.81 g, compared to 0.77 g on the second exposure.

EXPERIMENT 2 DISCUSSION

The objective of this experiment was to examine the effect of the RECAS warning on drivers who were not distracted. The results indicate that drivers benefit from the warning regardless of whether they are distracted or not. There were no interactions between distraction and warning except when floor effects were encountered (e.g., the percentage of collisions could not drop below 0%). This result suggests that undistracted drivers benefit from the warnings as much as distracted drivers. Both distracted drivers and undistracted drivers responded faster with the warning, and maintained a greater safety margin. The data show no evidence that warning an undistracted driver might undermine safety.

Figure 11 shows the relative benefit associated with the warning, with the largest effect due to the RECAS warning, followed by distraction and exposure. The absolute magnitude of the differences shows that having the warning is more beneficial than not being distracted, and that experiencing the collision event for the second time provides less advantage than having the warning or not being distracted. These results provide strong evidence that warning drivers even when they are not distracted can have substantial benefits in imminent collision situations.

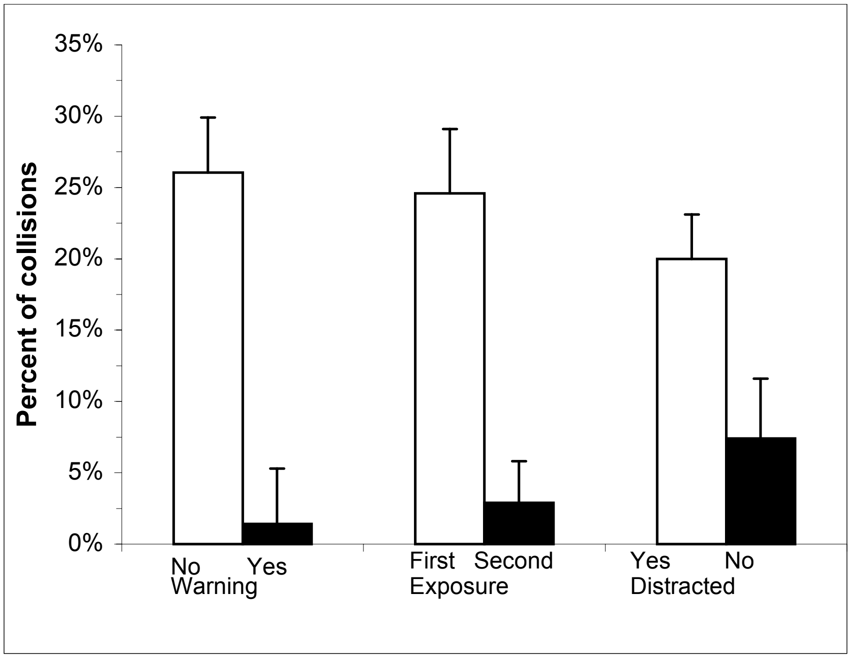


Figure 11. The relative effect of RECAS warnings, distraction, and exposure.

Although this experiment demonstrates a substantial benefit for warning undistracted drivers of imminent collision situations, it leaves several questions unanswered. Specifically, although the warning enhanced undistracted drivers' performance in the simulator, such warnings could be viewed as a nuisance to undistracted drivers if the system was installed in an actual car. A longer-term study is needed to understand how drivers' attitudes might evolve and affect the benefits observed. This study found no detrimental effect of warning undistracted drivers. However, it did not systematically explore the warning's potential to interfere with an ongoing braking response. Warnings issued as a driver responds might interfere with the response process and undermine the benefits of RECAS. As in Experiment 1, this experiment showed that the warning only reduced reaction time for the initial release of the accelerator. It did not affect the subsequent application of the brake. By manipulating the urgency of the auditory warning, it would be possible to further explore how the warning affects driver response. If the warning serves only to direct the attention to the road, a more urgent alert would not affect the response. Experiment 3 addresses this issue.

EXPERIMENT 3 METHOD

Purpose

The objective of this experiment is to investigate how drivers respond to warnings of imminent collision with different levels of urgency. Based on previous research showing that perceived urgency depends on loudness (Edworthy & Adams, 1996), three levels of urgency were defined for the auditory alerts.

Participants

Data were collected from 40 additional drivers between the ages of 25 and 55. Inclusion criteria were the same as in Experiment 1.

Apparatus

The apparatus was the same as in Experiment 1.

Experimental design

Like Experiment 2, Experiment 3 focussed on a subset of the experimental conditions in Experiment 1. Specifically, the low level of severity and the early- and late-warning conditions were examined. These conditions were chosen because they generated the lowest variance in Experiment 1, and so were expected to provide the most sensitive statistical comparisons. The data from drivers who were exposed to the two new volume levels were compared to data from the same conditions in Experiment 1. Table 6 shows the experimental conditions considered in Experiment 3. The drivers for this experiment were equally divided between the early and late warnings, and between the low and high warning volumes. Data for 40 drivers in the early and late warning conditions from Experiment 1 were used for comparison as the mid-range volume. For the low-volume warning tone (64.8 dB), the volume was 10 dB below that used in Experiment 1, whereas for the high-volume warning tone (84.8 dB), the volume was set 10 dB above that used in Experiment 1.

Dependent variables

The dependent variables were the same as in Experiment 1.

Table 6. Experimental conditions to examine the influence of warning urgency on driver response to the RECAS.

Condition	Initial velocity (mph)	Lead vehicle deceleration (g)	Initial headway (s)	Algorithm parameter	Volume
1	35	0.40	1.70	d_F=0.40 g	Low (64.8 dB)
2	35	0.40	1.70	d_F=0.75 g	Low (64.8 dB)
3	55	0.40	1.70	d_F=0.40 g	Low (64.8 dB)
4	55	0.40	1.70	d_F=0.75 g	Low (64.8 dB)
5	35	0.40	1.70	d_F=0.40 g	Mid (74.8 dB)
6	35	0.40	1.70	d_F=0.75 g	Mid (74.8 dB)
7	55	0.40	1.70	d_F=0.40 g	Mid (74.8 dB)
8	55	0.40	1.70	d_F=0.75 g	Mid (74.8 dB)
9	35	0.40	1.70	d_F=0.40 g	High (84.8 dB)
10	35	0.40	1.70	d_F=0.75 g	High (84.8 dB)
11	55	0.40	1.70	d_F=0.40 g	High (84.8 dB)
12	55	0.40	1.70	d_F=0.75 g	High (84.8 dB)

Procedure

The experimental protocol was identical to that used in Experiment 1.

EXPERIMENT 3 RESULTS

The effect of urgency, as operationalized by volume, had no statistically significant effect on any of the dependent measures. Volume had no effect on the safety benefit or on drivers' reaction time or brake application. High volume did not speed reactions nor did it interfere with drivers' responses by startling them. For all dependent measures, the F values were near or below 1 and the p values were above 0.05.

The adjusted minimum time to collision, which was one of the more sensitive measures in the previous experiments, was the only variable to show an effect of volume. Figure 12 shows the interaction of the warning timing and volume, $F(2,67)=3.54$, $p<0.05$. The magnitude of this interaction and the lack of any other parallel effects for the other dependent variables suggest that this may reflect only random variation in the data. The most direct measure of the effect of volume is the time of the accelerator release relative to the alert. The volume did affect the initial accelerator release, with the lowest volume generating the fastest reaction time (854 ms), compared to the moderate volume (1.36 s) and the high volume (1.02 s), $F(2,68)=3.77$, $p<0.05$. Volume also affected the initial accelerator release ($F(2,68)=3.75$, $p<0.05$) and the time from initial brake press to maximum brake press ($F(2,68)=3.71$, $p<0.05$) through three-way interactions among the order of the trials, the volume, and the timing of the warning. These interactions show no systematic pattern, with the majority depending on just two of the twelve conditions.

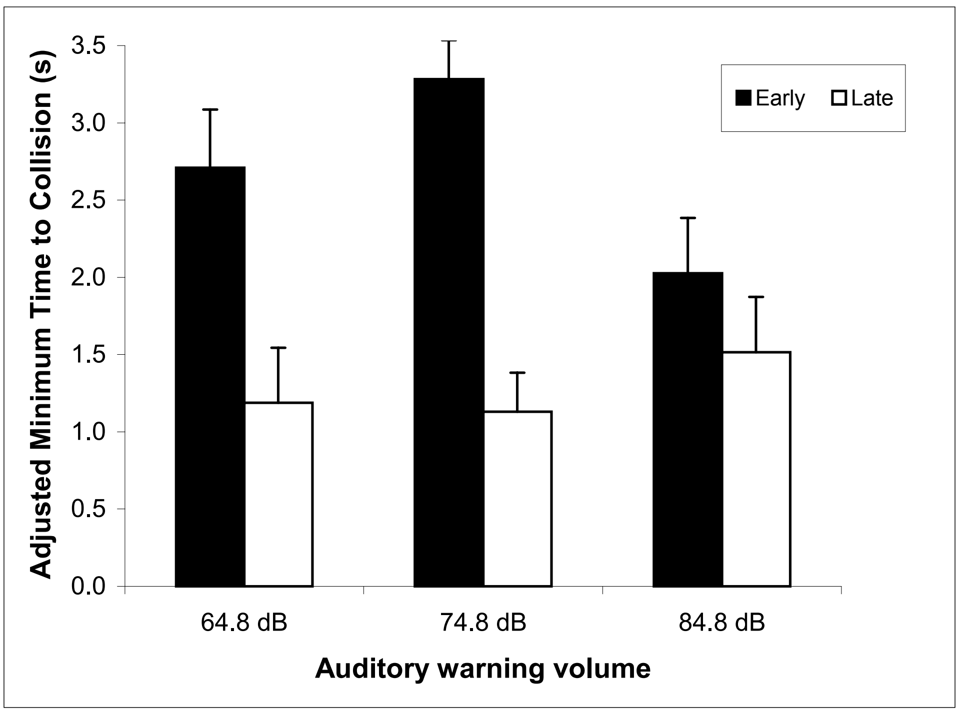


Figure 12. Warning volume interacts with warning timing to affect adjusted minimum time to collision.

Although volume failed to affect driver behavior, the experiment was sensitive to the dependent variables tested in Experiments 1 and 2. As in the previous experiments, the early warning provided a greater safety margin and induced a faster release of the accelerator. As in Experiment 2, the warning did not enhance the other elements of the response process. Also as in the previous experiments, the data revealed compensatory behavior in which drivers tended to brake faster and harder to compensate for slow initial responses and to brake slower and lighter when they had managed to achieve fast initial responses.

EXPERIMENT 3 DISCUSSION

The results confirm the hypothesis that RECAS warnings only shift drivers' attention to the road. If the warnings mediated driver response beyond shifting their attention to the road, more urgent warnings would have been likely to influence the response process. Specifically, a highly urgent warning would likely reduced the transition from accelerator to brake, as well as increase the speed of brake depression. The highly urgent warning might also have increased average and maximum braking. This experiment varied loudness over a wide range (20 dB) and found no statistically significant effects and no trends to suggest that volume might affect driver response. Because volume is the parameter of warnings that most reliably enhances perceived urgency, it is likely that other manipulations of urgency would have little effect on driver behavior. This result argues that warning tones should not be amplified in the hope that they will produce a faster response; however, this does not imply that lowering the loudness of tones will leave performance unaffected. Warning tones must be loud enough to avoid being masked by background noise.

GENERAL DISCUSSION

Benefits of warnings

For the imminent collision situations examined, drivers dramatically benefit from the RECAS warning. Overall, drivers with the RECAS experienced fewer collisions, less severe collisions, and had a greater margin of safety (a larger adjusted minimum TTC). These convergent measures demonstrate the benefit of RECAS warnings. The data also 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 to those who did not receive any warning. Distracted and undistracted drivers benefited equally from the warning. Beyond the direct benefit of avoiding collision with the lead vehicle, drivers who received the warning also decelerated more gradually. This more gradual deceleration could decrease drivers' risk of being struck from the rear. This may be an important consideration in a comprehensive benefits analysis. This study also shows that RECAS warnings enhance driver response over a wide range of headways, velocities, and lead vehicle decelerations. The convergent evidence strongly supports the contention that the RECAS algorithm used in this study could enhance driver response to potential collision situations.

Mechanisms underlying driver response to warnings

Hypothetically, RECAS warnings could enhance the speed of drivers' accelerator release, their transition from accelerator to brake, and their depression of the brake from initial brake press to maximum deceleration. Such warnings might also increase mean and maximum deceleration. The data from all three experiments, however, show that the warning enhances only the speed of the accelerator release. The warning seems to affect drivers' response only by returning their attention to the road. No other elements of drivers' response are enhanced by the warning. The finding that increased warning urgency does not affect drivers' response confirms these findings. If the warning did more than return drivers' attention to the road, increased urgency could be expected to speed drivers' response. Instead, urgency had no systematic effect on the response, suggesting that RECAS warnings do serve to return drivers' attention to the road.

The results also show that drivers adapt their responses after the initial accelerator release. Drivers who released the accelerator relatively late intensified their braking behavior, moving to maximum braking more quickly and using higher levels of braking. These results demonstrate that drivers' braking response is a closed-loop control process, where braking is adjusted based on the evolving collision situation. This suggests that accurate driver performance models must also include this closed-loop control process. By broadening the 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 in turn can help evaluate RECAS effectiveness.

Degree of surprise experienced by drivers

An important consideration in generalizing the results of this study is the degree to which the braking events truly surprised drivers. Anecdotally, drivers' facial expressions registered a distinct note of surprise at the first braking event. In addition, their eyeglance patterns suggested that most were attending to the in-vehicle task and were not expecting the lead vehicle to brake.

Likewise, the generally poor collision avoidance performance suggests that they were surprised by the event. Under conditions in which drivers were not distracted by the in-vehicle task, evidence also suggests that they were nonetheless surprised by the braking event. Collision avoidance behavior in the undistracted conditions was not perfect and the warning enhanced drivers' ability to avoid collisions. Eyeglance and collision avoidance behavior did change substantially from the first to the second trial, suggesting less surprise on the second trial. Defining an absolute measure of the degree of surprise is difficult, but the surrogate measures of collision avoidance performance, benefit of the warning, and eyeglance behavior all suggest that drivers were surprised by the sudden onset of braking by the lead vehicle.

Model-based extrapolation of results

This simulator study examined only two combinations of assumed deceleration and reaction time. The combinations that were considered were a 1.5 s assumed reaction time combined with both 0.4 g and 0.75 g assumed deceleration. Using a model of the driver developed to examine rear-end crash scenarios, it was possible to extend the analysis beyond the values tested in the simulator. The model used in this evaluation was the Attention-based Rear-end Collision Avoidance Model (ARCAM) (Brown & Lee, 2000; Brown, Lee, & McGehee, in press) that is based largely on Gibson's Field Theory of driving (Gibson & Crooks, 1938). The model provides a theory-based extrapolation of experimental results. This model-based analysis examined levels of assumed driver reaction time from 1.0 s to 2.0 s in 0.25-s increments, while also varying assumed deceleration from 0.20 g 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.

The data from this analysis were collected and a contour plot was generated based on the percentage of collisions for each combination of algorithm parameters. The contour plot is shown in Figure 13. When high assumed decelerations are paired with low assumed decelerations, the probability of collision is greatest. A promising combination of assumed reaction time and assumed deceleration is around 1.5 s and 0.4 g. The areas with high probability of collisions are not in close proximity to this area. Although other regions with low probability of collision could be examined, those areas closest to the higher rates of collision could be more susceptible to inaccuracies in the model and variations in the driving situation.

Further model-based analysis should be conducted to identify how the parameters affect false alarms. By creating an objective function that reflects the costs of false alarms and the benefits of detecting a collision situation a similar contour plot could be created to identify the optimal algorithm parameters.

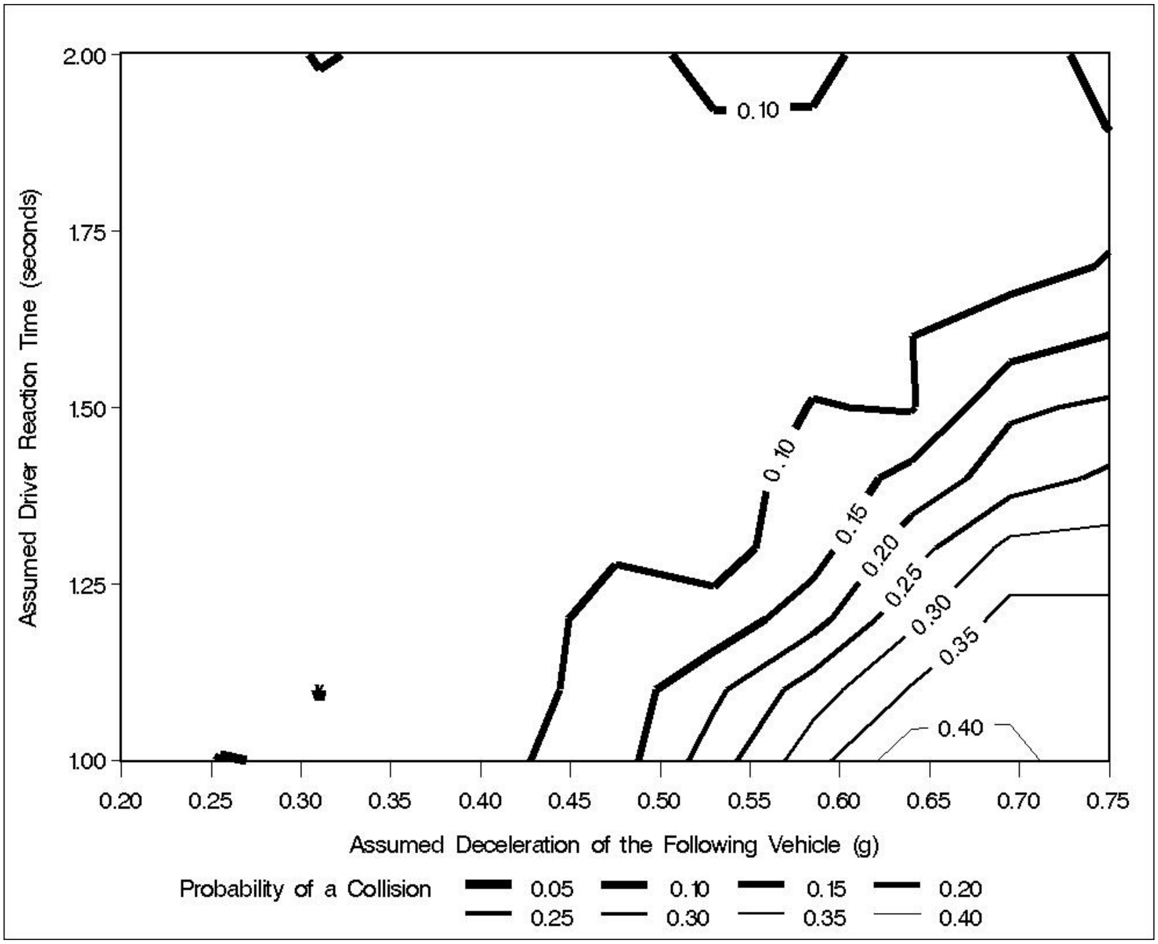


Figure 13. Contour plot of probability of a collision for the algorithm parameter space.

CONCLUSIONS, DESIGN RECOMMENDATIONS, AND FUTURE RESEARCH

This study contributes to methods used to evaluate in-vehicle warning systems and provides guidance regarding algorithm and display design. It should be noted, however, that the usefulness of these conclusions depends on how well driver behavior in a simulator generalizes to actual on-road driving. Because this study was conducted in a simulator, drivers were not exposed to the same risk as on an actual roadway. The lack of any severe consequence may have affected drivers' behavior; however, informal observations suggest that the drivers where fully engaged and immersed in driving. They reacted as if they were in actual collision situations. The results are 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 may have greatly influenced how multiple exposures affected responses to unexpected events. Furthermore, this study exposed drivers to the collision warning system for approximately 30 minutes and did not consider long-term adaptation. It is possible that longer exposure could either enhance or degrade the safety benefit of the warning. These studies also considered a limited range of collision situations, algorithm parameters, and driver interface options. In particular, this study exposed drivers to very severe situations. In normal driving, such situations are quite rare and the overrepresentation of these situations in this experiment should be considered when extrapolating the results and estimating crash reduction benefits for the driving public. Thus, care is required in extrapolating to general design considerations. Even with these caveats, this study has important implications for system evaluation, algorithm design, and driver-vehicle interface design.

System evaluation

This study used repeated exposures to collision situations to evaluate the effectiveness of a RECAS warnings. Three criteria provide a basis for evaluating the utility of this approach. Applying these criteria suggests that data from multiple exposures should be considered with care, but that multiple exposures can provide meaningful data. The first and most important criterion for judging the validity of multiple exposures is the interaction between exposures and RECAS conditions. The data show no interactions. The second criterion concerns how the exposure might affect the dynamics of the drivers' response. The data show that subsequent exposures lead drivers to devote additional attention to the roadway. This increased attention to the road translates into a 430 ms faster accelerator release. The faster initial response allows the drivers to avoid a panic braking situation—they can reach maximum braking more slowly and stop with a lower mean and maximum deceleration. Thus, while multiple exposures do not change the fundamental response dynamics, they do affect performance by changing how drivers monitor the roadway in the face of the distraction task. The third criterion is that the outcome does not change with repeated exposure. The data show that, in this experiment, multiple exposures violated this criterion and that drivers reacted more quickly and avoided more collisions after the first exposure.

Because there were no interactions and the dynamics of the drivers' response did not change, it may be possible to adjust statistically the reaction time to the second exposure by 430 ms, the amount that drivers' reaction time decreased from the first to the second exposure. Incorporating these results into a statistical or computational model of driver behavior could further enhance the information available in a multiple-exposure experiment. Although the results of this study are promising, they do clearly indicate that a second exposure is not equivalent to the first, and that the data from any multiple-exposure experiment must be carefully examined to ensure that these differences do not jeopardize the validity of the data.

Algorithm design

The results show that a RECAS can greatly reduce the chance of collision in the scenarios tested. Not surprisingly, an early warning provides a greater benefit than a late warning; however, the operational implications of this benefit depend on the effect of the early warning on nuisance alarms. Further data collection in operational settings is required to assess driver response to the nuisance alarms generated by early warnings. The data from this experiment could provide input into a tradeoff analysis to assess if the benefit of an earlier warning merits the additional nuisance alarms it generates. The very large potential safety benefit seen for distracted drivers provides preliminary evidence to suggest that RECAS may be especially beneficial to drivers distracted by in-vehicle technology (e.g., cellular telephones). The potential safety benefit of these systems will likely increase as in-vehicle information systems proliferate and increase the likelihood of driver distraction. Algorithm design might consider adjusting the threshold of warnings based on an estimate of driver distraction, such as the state of the cellular telephone. Such a strategy could also provide large safety benefits. These design implications must be tempered by an acknowledgment of the limited data collected as part of this study. Additional research could verify these design suggestions. Some specific research issues include:

- Identifying why some drivers ignore the warning and the factors affecting compliance;
- Evaluating whether or not a warning that occurs during a driver's response disrupts performance;

- Evaluating how nuisance alarms and failures to detect potential collision situations affect appropriate compliance with the warning;
- Developing a Monte Carlo model to consider how parameter values affect the cost of nuisance warnings relative to the benefits of early warnings;
- Examining how drivers' response to warnings changes with extended exposure to the RECAS; and
- Identifying how well warnings mitigate potential distractions associated with in-vehicle information systems.

Driver-vehicle interface design

This study shows that a simple driver-vehicle interface, composed of a small icon and an auditory warning tone, does not induce a startle response or otherwise impair driver performance. The study also shows that RECAS warnings do not appear to require any special considerations to avoid startling the driver. Warnings that adhere to basic human factors principles with regard to onset speed and volume do not startle either distracted or undistracted drivers. The warning tone was effective in directing driver attention to the road and the braking lead vehicle. Increasing the perceived urgency of the tone, assuming urgency increases with volume, had no effect on driver response. Therefore, it may be more useful to focus future efforts on minimizing the perceived annoyance of warnings rather than on increasing warning urgency. A warning tone of approximately 75 dB appears adequate to alert drivers and higher volumes do not appear to provide a benefit. These design considerations are based on very limited range of interface options. Specifically, urgency was manipulated only by increasing the volume of the warning tone, and only a single icon and tone were tested. If urgency were to be evaluated in a context that included warnings from other systems (e.g., side object detection, navigation system, and cellular telephone), urgency and other characteristics that help drivers interpret the meaning of auditory alerts could become more important. The range of potential interface alternatives is enormous, and the effect of these alternatives on driver performance and acceptance is poorly understood. Several particularly important research issues include:

- Examining the potential for haptic and tactile cues to reduce potential annoyance and to speed reaction time;

- Verifying the finding that urgency does not affect driver response with a wider range of tones, a greater number of potential alerts, and a wider range of parameters that affect urgency; and
- Examining how the interface for adaptive cruise control, headway maintenance, cautionary alerts, and imminent collision warnings should be integrated.

ACKNOWLEDGEMENTS

This research was sponsored by the National Highway Traffic Safety Administration, Contract DTNH22-95-D-07168 IQC #2(8-07633). Special thanks to Mike Perel, August Burgett, Wassim Najm, Robert Miller, and David Smith for their helpful comments on the design and conduct of this study. Also, we would like to acknowledge the dedicated effort of those who coded the videotape data: Kristi Schmidt, Robert Betts, and Josh Hoffman.

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APPENDIX A: RECAS DRIVER PERFORMANCE GRAPHS

As part of this study, data files from Iowa Driving Simulator were manipulated using Matlab 5.0 to produce two graphs of each driver's performance during each drive. These graphs make it possible to examine the dynamics of driver responses that may not be captured when the data are aggregated according to experimental conditions. Specifically, the graphs reveal the closed-loop nature of driver responses. They also provide a detailed view of driver responses that can be used to identify the prevalence of a startle response. The first graph is a timeline plot that shows the driving environment and driver response over time. The second graph is a phase space that shows the range and range rate over time, which is helpful to visualize the statiotemporal dynamics of the two vehicles.

Description of the two graphical representations

For the timeline plots, the x-axis is time in seconds. The graph begins two seconds before the lead vehicle begins to brake. The point at which the lead vehicle begins to brake defines the zero point on the timelines. The graph ends after the threat of collision has passed. Figure 14 shows an example of a timeline graph.

The data presented in the timeline graphs include the velocities of both the lead and subject vehicles, the positions of the accelerator and the brake pedal, and the time to collision (TCC). In addition, if a warning occurred, there is a spike at the time the alarm sounded. The velocities of the vehicles are in units of m/s divided by a scaling factor of 30. The accelerator and brake pedal positions are normalized so that 1 equals the maximum possible pedal depression. TCC is a continuous measure defined as the length of time until collision if the two vehicles continue to travel at their current relative velocities and decelerations. Before the lead vehicle begins to brake, its velocity is the same as the subject vehicle velocity, and they are separated by a constant headway. They would never collide if they continued to travel under the initial conditions, causing TCC to be infinity. Since infinity cannot be graphed, TCC is coded as a negative value before the lead vehicle begins to brake. When this event occurs, collision becomes possible and TCC assumes its true large positive value. As the collision situation evolves TCC fluctuates, showing the severity of the collision threat. If the two vehicles collide, at that point they travel at approximately the same velocity and TCC again approaches infinity, so TCC is again graphed as a negative value. TCC also becomes negative when the velocity of both vehicles is zero.

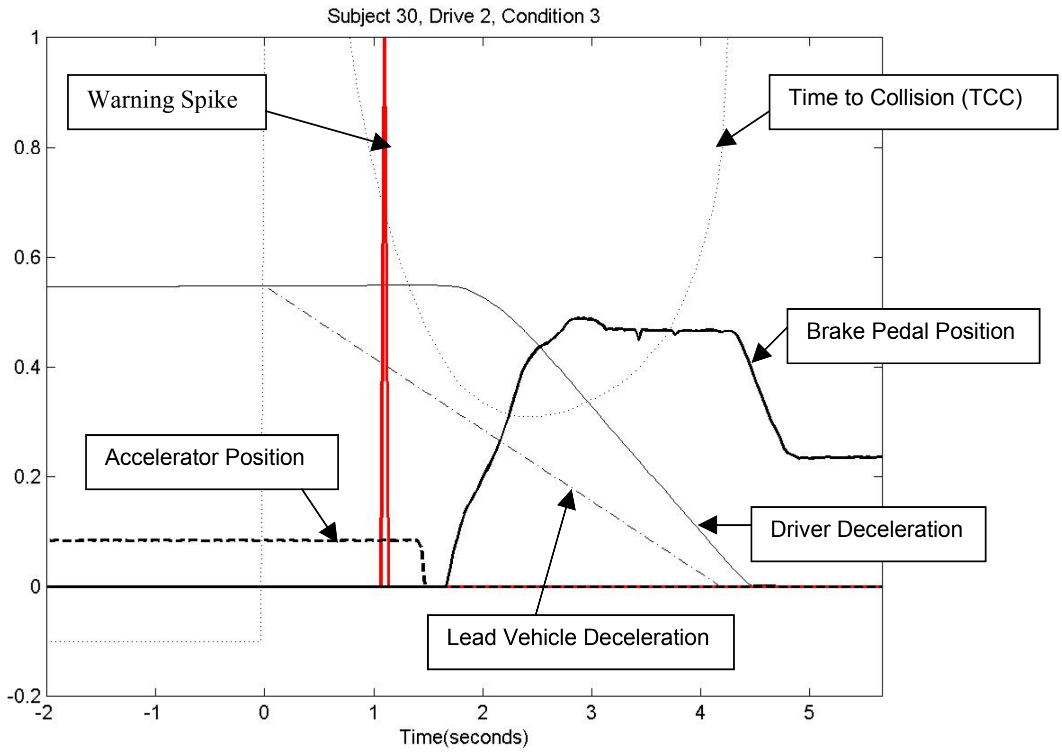

Figure 14. An example of a timeline graph.

The range rate vs. range graphs plot the instantaneous distance between the two vehicles (range, y-axis) against the difference in the velocities of the two vehicles, also known as the relative velocity (range rate, x-axis). Figure 15 shows an example rate vs. range graph. The shape of this curve describes how the driver responded. If the slope of the driver's velocity in the timeline plot is constant, showing constant deceleration, then the shape of the range rate vs. range graph is an elongated parabola that is open to the left. If the slope of the velocity is not constant, the parabola shape will be deformed or distorted. If the subject vehicle stopped before the lead vehicle, the bottom portion of the graph after the subject vehicle stops is a straight vertical line in the negative range rate region. The range rate is negative because the lead vehicle velocity is greater than zero (the velocity of the subject vehicle). If a collision occurred or the driver steered around the lead vehicle, the range goes to zero while the range rate is still positive.

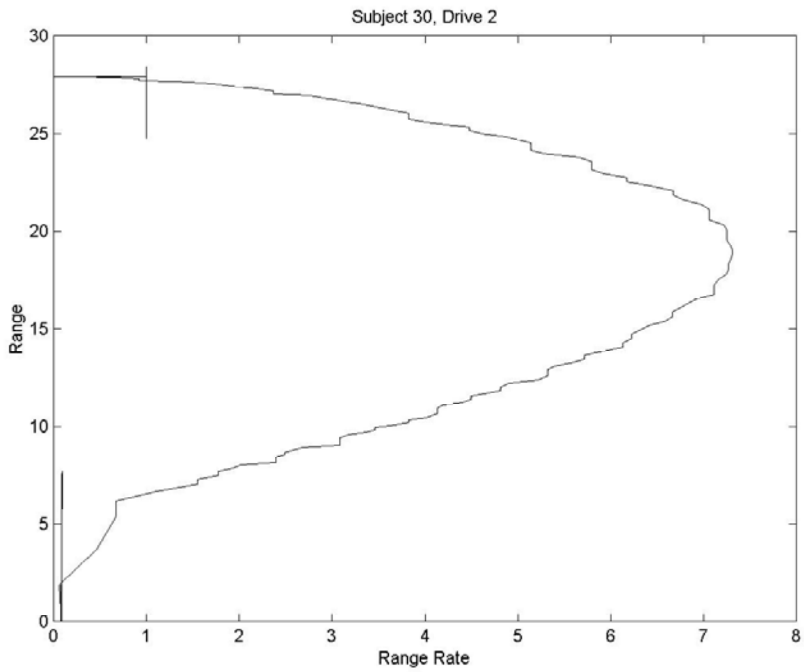

Figure 15. An example of a range rate vs. range graph.

Several driver-response-process variables are visible on the graphs, including accelerator-release time, accelerator-to-brake transition time, and initial brake-to-maximum brake time. The safety benefit measures of whether or not the two vehicles collided, the vehicles' relative velocities at the time of collision, and TTC are also present. However, the graphs reveal other trends and driver behaviors. Through the graphs, we can see that drivers used different braking responses under certain conditions, and that the warning did not induce a startle response.

Evidence for closed-loop modulation in the braking response

The lines representing the accelerator and brake pedal positions clearly show the driver's response. The graphs are particularly helpful in understanding the response strategies identified in the cluster analysis. For cluster 1, which mainly contained high velocity/early warning conditions, approximately 80% of drivers modulated their response by applying and releasing (partially or completely) the brake pedal at least once or by pausing during their braking response. In other words, they did not apply constant pressure to the brake. Figure 16 shows an example of how drivers modulated their braking responses. Graphs from cluster 2 (the majority of these drivers received an early warning) show that approximately 65% of drivers modulated their braking response. In contrast, only around 30% and 15% of drivers in clusters 5 and 6, respectively, modulated their response. Most of the drivers in these clusters received the warning late or not at all. About 50% of the drivers in clusters 3 and 4 demonstrated modulated braking behavior. These data show that because drivers were aware of the braking lead vehicle early, they were able to perceive cues from the environment and could respond to the situation in a gradual, controlled manner. In this way, modulation of braking behavior correlates negatively with collisions. In addition, a modulated, more controlled braking response may reduce their chances of being hit from the rear by a third car.

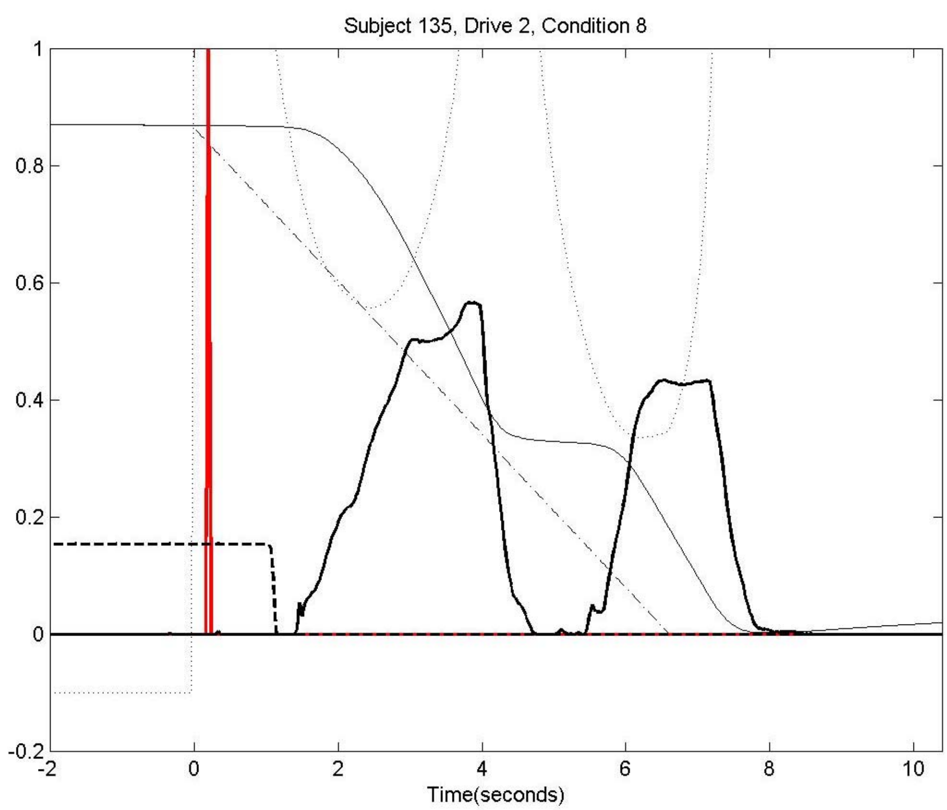

Figure 16. An example of a modulated braking response.

RECAS warnings, startled response, and disruption to non-braking behavior

The graphs also provide evidence that the RECAS warning does not produce a startle response while the driver is not braking. Very few graphs (less than 5%) in all three experiments show any change in driver response during or immediately following the warning spike. Four drivers released the accelerator very abruptly (less than) when the warning was initiated. Five drivers released the accelerator a bit more gradually (in less than 500ms). One driver in the process of releasing the accelerator in this manner released it more abruptly when the warning sounded. Two drivers abruptly depressed the accelerator during the initial moment of the warning.

The behavior of these 12 drivers in the moments following the warning suggests that a RECAS warning may induce a rapid response; however, the data do not show any major disruption of ongoing responses due to the warning. Since the responses of these 12 drivers represent less than 5% of the 278 drives in which the warning sounded and the driver was not braking, these data suggest that "startle" responses during non-braking behavior are unlikely. In addition, it is difficult to ascertain here if the warning caused the accelerator release in these cases or if the drivers' responses simply coincided with the warning. The warning may have had no effect on the specific responses discussed here. Finally, only one of these drivers had a collision and it was minor one, suggesting that the warning did not impede driver response.

Further study of effect of warning during braking needed

When the warning sounded, two out of 280 scenarios, involved drivers braking as the warning sounded. One driver had already begun to release the brake pedal. When the warning sounded, this driver depressed the brake pedal rapidly. Figure 17 shows one of the few examples of a potential startle response to the warning signal. The warning seemed to have no effect on the other driver. Neither driver collided with the lead vehicle. 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. Clearly further research is needed to determine whether the RECAS warning interferes with the braking response.

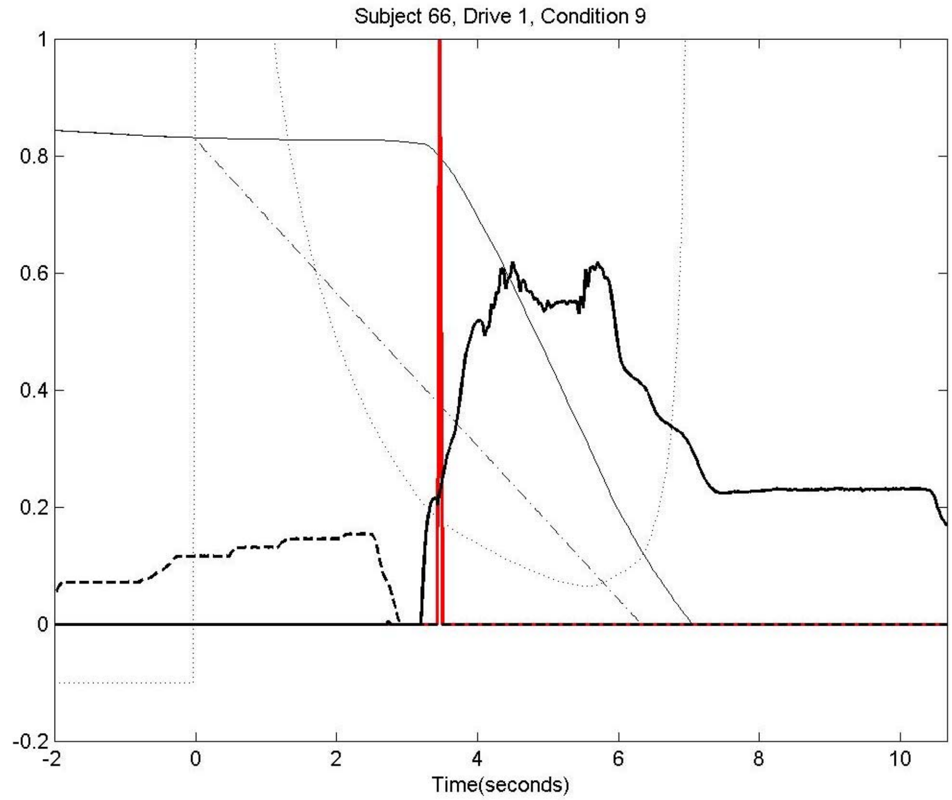

Figure 17. One of the few suggestions of a startle response during braking.

Conclusion

The graphs of driver performance created by Matlab clarify drivers' responses and give detailed information about how drivers responded in the simulator environment. Without this visualization, certain aspects of driver behavior would be very difficult, if not impossible, to obtain. In this study, analysis of the graphs of driver performance revealed modulated braking behavior, evidence that RECAS warning does not cause a startle response during non-braking driving behavior. The graphs also suggested that further study of the startle response is necessary for situations when the driver is braking.

DOT HS 809 448
March 2002

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