U.S. Department
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**National Highway
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DOT HS 810 981 **August 2008**

Rear-End Crash Avoidance System (RECAS) Algorithms and Alerting Strategies:

Effects of Adaptive Cruise Control and Alert Modality on Driver Performance

Final Report

1. Report No.
DOT HS 810 981

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Rear-End Crash Avoidance System (RECAS)
Algorithms and Alerting Strategies:
Effects of Adaptive Cruise Control and Alert Modality
on Driver Performance

5. Report Date
August 2008

6. Performing Organization Code

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8. Performing Organization Report No.

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University of Iowa
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10. Work Unit No. (TRAIS)n code

11. Contract of Grant No.

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
1200 New Jersey Avenue SE.
Washington, DC 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative: Michael Perel.

16. Abstract
Adaptive cruise control (ACC) represents a rapidly emerging in-vehicle technology that has the potential to enhance driving safety. A critical factor governing the safety benefit of ACC concerns the ability of the driver to assume control of the vehicle in situations that exceed the capability of ACC. This study examined the effectiveness of various warning modalities in reengaging drivers who were likely to be distracted during severe braking situations that exceed the capability of ACC. The study compared warnings that paired a visual icon with an auditory cue, seat vibration, brake pulse, or a combination of all three cues. A total of sixty participants drove for 35-minutes in the National Advanced Driving Simulator (NADS). Drivers experienced 2 severe, 4 moderate, and 8 mild braking situations. The ACC could accommodate all but the 2 severe situations without driver intervention. ACC provided a substantial benefit during mild braking lead vehicle events, enabling drivers to maintain a larger and more consistent minimum time-to-collision. In contrast to previous studies (e.g., Stanton, Young, & McCaulder, 1997), ACC did not produce a safety decrement during the severe braking situations. Only the combination of visual, auditory, seat vibration, and brake pulse led to slower brake reaction time in severe braking situations compared to drivers without ACC, but all four warning strategies led to a similar minimum time-to-collision and maximum braking. In contrast to several previous studies, these results suggest that drivers can effectively assume control when they receive a warning that the braking authority of ACC has been exceeded. Further research is needed to identify the boundary conditions that specify when drivers can successfully intervene and retake control and whether a multi-modal combination of cues can be crafted to speed rather than slow drivers' response.

17. Key Words
Adaptive cruise control
Warnings
Automation
Driver reaction

18. Distribution Statement
This report is free of charge from the NHTSA Web site at www.nhtsa.dot.gov

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of Pages

22. Price

Technical Report Documentation Page
Form DOT F1700.7 (8-72)

Reproduction of completed page authorized

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INTRODUCTION

New technology is changing the task of driving in ways that can potentially enhance driving safety. Technology that actively intervenes and controls the speed or direction of a vehicle may have the greatest effect on safety. Adaptive cruise control (ACC), augmented braking, and steering assist systems all represent technology that could actively intervene to augment human perceptual-motor capabilities and enhance driving safety. Of these, ACC is becoming widely available in production passenger vehicles.

ACC operates much like conventional cruise control when there are no other vehicles in front of a driver. When an ACC-equipped vehicle comes upon slower moving vehicles, however, ACC uses vehicle-based sensors to estimate the distance and velocity relative to the vehicle ahead and then modulates the accelerator and service brakes to maintain a set time headway from the lead vehicle (Fancher, Bareket, Bogard, MacAdam, & Ervin, 1998). As ACC is designed as a convenience system rather than as a safety system, it does not engage the full braking potential of the vehicle. This design goal likely reflects current capacity of the technology relative to the expectations of a safety system. A safety system might need to satisfy higher performance standards than a convenience system. In situations that require severe braking, the system alerts the driver to the need to intervene to avoid striking the moving or stationary vehicle (McGehee, LeBlanc, Kiefer, & Salinger, 2002; Sayer, 2003). This warning serves as a forward collision warning (FCW), and in combination with ACC, it could substantially improve drivers' ability to maintain safe speeds and headways and to avoid collisions.

Although offered as a convenience system, ACC may deliver an added safety benefit because it can provide a rapid response if the lead vehicle slows. The response time of ACC, approximately 300 ms, to a braking vehicle can be substantially less than that of a typical driver. ACC may also provide indirect benefits in that ACC braking is less abrupt and variable than that of a typical driver. ACC can attenuate traffic disturbances that a driver might otherwise accentuate (Bose & Ioannou, 2003; Ioannou & Stefanovic, 2005; Vahidi & Eskandarian, 2003). Such disturbances can contribute to crashes and induce congestion. In one traffic simulation model, congestion occurred when 10 percent of the vehicles engaged ACC, but no congestion occurred when 20 percent of vehicles engaged ACC (Davis, 2004). This difference points to the potential of ACC to control headway more precisely and moderate traffic disturbances better than drivers.

However, because people do not always rely on automation appropriately, even relatively simple automation, such as ACC, has the potential to undermine driving safety. In other domains, automation with a high level of authority and little feedback has been found to degrade event detection and slow response (Endsley & Kiris, 1995; Sarter & Woods, 1995, 1997; Wickens & Kessel, 1981). Likewise, poor feedback and imprecise mental models of automation can lead to miscalibrated trust in system capability, increased complacency, and inappropriate reliance (Lee & Moray, 1994; Lee & See, 2004; Parasuraman, Mouloua, & Molloy, 1994). As a form of automation that offers relatively little feedback and operates with a high level of authority, ACC may cause similar problems and so may undermine driving safety. In one simulator study, approximately one third of drivers were not successful in assuming control after the ACC had failed (Stanton et al., 1997). Distractions associated with cell phones and other in-vehicle technology may exacerbate this effect by encouraging drivers to rely on vehicle automation and neglect the driving task.

Feedback regarding ACC status helps drivers determine when they must intervene and encourages them to develop accurate expectations of ACC behavior (Stanton & Young, 1998). Depending on the algorithm, drivers will experience mild to moderate decelerations with the onset of ACC braking. The haptic and vestibular cues associated with these decelerations depend on the control algorithms of the ACC system and could serve as an early warning of a traffic situation that requires intervention. However, if these decelerations are too pronounced based upon the proximity of the vehicle being approached, drivers may interpret the cues as overly harsh and annoying, unless the deceleration is truly needed.

Detecting decelerations and managing the transitions from ACC to driver control are easiest if the operational limits of ACC correspond to the natural boundaries between speed regulation/car-following and active braking (Goodrich & Boer, 2003). Such boundaries can be defined in terms of a perceptual phase space in which time headway (range between the vehicles divided by the velocity of the driver's vehicle) defines the horizontal axis and the inverse time to collision (the relative velocity divided by the range) defines the vertical axis. Braking behavior of skilled drivers exhibits a smooth counterclockwise trajectory in this space. ACC braking behavior that fails to follow such a trajectory may undermine drivers' ability to intervene appropriately (Goodrich & Boer, 2003). Figure 1 shows examples of consistent and inconsistent braking behaviors.

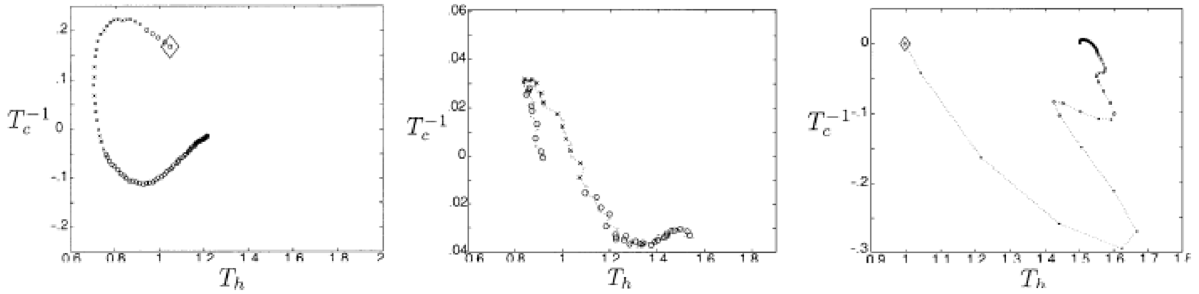

Figure 1. A perceptual phase space defined by the inverse of time to collision (T_c^{-1}) and time headway (Th) (Goodrich & Boer, 2003). The panel on the left represents the behavior of a professional driver and the panels on the right represent unacceptable ACC behavior.

Even if transitions from ACC to driver control correspond to natural boundaries (e.g., where braking is clearly required), drivers may need alerts to signal the need to intervene. The alert type could have an important influence on driver performance and acceptance. Potential alerts include auditory cues, such as tones or verbal notices; haptic cues, such as seat vibrations and brake pulses; and visual displays, such as heads-up displays or icons located in the instrument cluster (Graham, 1999; Hirst & Graham, 1997; Lee, Hoffman, & Hayes, 2004). Warnings often combine these cues, but little research has addressed multi-modal warnings for ACC. Standards such as Society of Automotive Engineers (SAE) J2399 simply describe algorithmic issues and indicate that drivers should be warned when the ACC's braking authority is exceeded (Sayer, 2003).

Of the possible collision warning cues, haptic cues have great potential, but are least investigated. Haptic cues may be more congruent with expected driver response—a brake pulse naturally draws attention to the brake and has a greater degree of stimulus-response compatibility compared to an auditory tone that has no natural association with braking (Wickens, Lee, Liu, & Gordon, 2003). This consideration may become increasingly important as alerts from other in-vehicle information systems proliferate. Another critical issue concerns how the alert modality affects driver response to inappropriate alerts. Inappropriate alerts are those that are not related to a safety-relevant event. Haptic alerts might be particularly likely to induce braking responses to inappropriate alerts, and preliminary evidence suggests some people may be particularly prone to such inappropriate responses—one participant out of a group of seven accounted for 40 percent of the inappropriate braking responses in one study (Tijerina et al., 2000). Currently produced vehicles use auditory and visual cues when situations exceed the braking authority of ACC, and relatively little research has considered the potential benefit of haptic cues for collision warning devices (Ho, Tan, & Spence, 2005).

The objective of this study is to assess drivers' ability to transition from ACC to manual control when warned with alerts of different modalities. This study compares headway maintenance performance for drivers with and without ACC during mild, moderate, and severe braking events. Specifically, this research examines the effectiveness of warning modalities (visual, auditory, seat vibration, brake pulse, and a combination of all of these) in supporting driver response to situations requiring severe braking in two different crash scenarios (a braking lead vehicle and an abrupt lane change of a lead vehicle that reveals a slow-moving vehicle). A secondary objective is to assess the degree to which alert modality affects drivers' compliance with inappropriate alerts.

METHOD

Sixty people drove in a high-fidelity driving simulator and experienced 8 mild, 4 moderate, and 2 severe events over the course of a 35-minute drive. They drove at the posted speed of 65 mph (105 kph) and experienced situations in which the ACC or warning system responded when it should not have. In one of these situations, the forward collision warning system (FCW) delivered an inappropriate alarm, and in six other situations the ACC braked inappropriately. One group of 12 participants drove a vehicle equipped with only an FCW, which consisted of a visual and auditory warning. Four groups of 12 participants drove with ACC and had an FCW that provided a visual alert in combination with either an auditory, seat vibration, or brake pulse cue, or a combination of all cues. The group with only the FCW received an auditory and visual warning during the same severe braking situations, as well as in the mild and moderate braking situations if they did not respond in a timely manner. During the drive, participants were periodically asked to complete a visually demanding task that required them to take their eyes off the road for extended periods. The purpose of this task was to distract drivers when they were required to brake, and braking events were triggered by drivers initiating the task.

Participants

Sixty people age 30 to 50 (*M*= 41.7; *SD*= 42.0) and balanced by gender participated in this study. Participants were screened so that they all drove at least 4,500 miles per year, held valid drivers' licenses, and used cruise control at least twice per month. The total participation time for each person was approximately 105 minutes. Participants completed a demographic questionnaire and received pre-drive instructions that took approximately 25 minutes to administer. Following the verbal instructions, participants drove a 6-minute practice drive, followed by a 35-minute experimental drive. Participants were paid $20/hour with a total compensation of approximately $40.

Experimental Design

A mixed between-within experimental design assessed the effect of warning modality and braking events. Each participant experiences each level of a within-subject variable, but only one level of a between-subject variable (Wickens et al., 2003). The warning mode was a between-subject variable and had four levels: auditory, seat vibration, brake pulse, and a combination of all three. All warnings also included a visual alert. In a fifth condition, one group of participants drove without ACC, but had a FCW with an auditory and visual warning that was the same as the auditory and visual warning of those driving with ACC. In this condition, the braking events were matched to the ACC conditions by gradually coupling the lead vehicle to the participant's vehicle five seconds prior to the onset of the severe and moderate events. The lead vehicle and the participant's vehicle were coupled by programming the lead vehicle to assume and then maintain a 2-second headway just before the braking event. Providing no warning or other feedback when the braking authority of the ACC has been exceeded is a logical alternate condition that might have been investigated in this experiment; however, we did not consider this experimental condition because it is inconsistent with existing standards (Sayer, 2003).

The experiment also included event type, event severity, and response appropriateness as within-subject variables. Event type differentiated events in which the lead vehicle braked (braking lead vehicle) from events in which the lead vehicle changed lanes to reveal a slow-moving vehicle (revealed lead vehicle). Response appropriateness refers to whether the ACC/FCW system responded to the traffic situation appropriately. For drivers in the condition with only FCW and no ACC, inappropriate responses were FCW warnings that occurred without a corresponding need to brake. For drivers in the ACC conditions, inappropriate responses also included unnecessary mild and moderate deceleration by the ACC. Similar to the drivers in the no-ACC condition, inappropriate responses to severe events in the ACC condition included inappropriate braking and a FCW warning without a corresponding need to brake. These inappropriate warnings occurred once for each driver. The inappropriate alerts occurred in response to overpasses, curves, and vehicles in the adjacent lane. Table 1 summarizes the events that define the within-subject conditions. Two orders of events were developed and counterbalanced such that half the subjects in each of the between-subject conditions experienced one of the orders.

Table 1. Summary of events experienced by each driver.

Event Type	Event Severity	Initial Time Headway (sec)	Initial Distance (ft)	Initial Lead Vehicle Speed (mph)	Lead Vehicle Decel.	Decel Duration	Duration of Constant Speed (sec)	Lead Vehicle Accel. (g)	Times
Revealed Lead Vehicle	Mild	3.2	305	45	n/a	n/a	3.75 s	0.3 g	4
	Moderate	3.2	305	30	n/a	n/a	3.75 s	0.3 g	2
	Severe	3.2	305	20	n/a	n/a	6.0 s	0.3 g	1
Braking Lead Vehicle	Mild	2.0	190	65	0.2 g	1.5 s	2.0 s	0.3 g	4
	Moderate	2.0	190	65	0.4 g	2.5 s	2.5 s	0.3 g	2
	Severe	2.0	190	65	0.7 g	2.25 s	3.0 s	0.3 g	1
Inappropriate Response	Mild	2.0	190	65	n/a	n/a	n/a	n/a	4
	Moderate	2.0	190	65	n/a	n/a	n/a	n/a	2
	Severe	2.0	190	65	n/a	n/a	n/a	n/a	1

The rightmost column of Table 1 shows the number of times each event occurred. Each driver experienced 8 events that were mild and required a deceleration of approximately 0.15 g; 4 events were moderate and required a deceleration of approximately 0.3 g; and 2 were severe and required a deceleration of more than 0.6 g. All but the severe braking events could be accommodated by the ACC without driver intervention. However, the ACC braking authority was limited to .25 g. As a consequence, if drivers did not intervene in moderate events the time-to-collision (TTC) would reach a minimum of approximately 2.4 seconds in the revealed lead vehicle scenario and 5.5 seconds in the braking lead vehicle scenario. Minimum TTC was calculated by dividing the distance to the lead vehicle by the relative velocity of the two vehicles. Minimum TTC represents the time it would take for the vehicles to collide if the relative velocity was to remain constant. Severe events required the driver to intervene to avoid a collision.

The moderate and severe events both triggered a warning if drivers did not intervene and kept the ACC engaged. Mild braking events did not trigger a warning because the ACC was able to slow the vehicle sufficiently to avoid crossing the threshold for the warning. The warnings occurred 3.5 and 1.7 seconds after the start of the moderate and severe revealed lead vehicle events, and 2.0 s and 0.7 seconds after the start of the moderate and severe braking lead vehicle events. The start of the revealed lead vehicle event was defined by the moment the lead vehicle began to change lanes to reveal the slow moving vehicle. The onset of the warnings highlights an important difference in the response of drivers and the ACC/FCW system. Drivers are relatively insensitive to the looming cues during the initial braking of the lead vehicle (Hoffmann & Mortimer, 1994, 1996), whereas the cues associated with a vehicle changing lanes are relatively salient. In contrast, the FCW responds quickly to the braking lead vehicle. An attentive driver might respond more quickly than the ACC/FCW during the revealed lead vehicle events, but not during the braking lead vehicle events.

In addition to the 14 events that required a response from the ACC or the driver, drivers were also exposed to 7 instances where the ACC responded as if there were a traffic event, but there was none. These inappropriate responses on the part of the system involved mild or moderate braking, and in one instance, triggered the FCW alert. Drivers with only the FCW received a single inappropriate warning, corresponding to the last line in Table 1. Overall, drivers were exposed to only 2 severe braking events and 1 inappropriate warning during the 35-minute drive.

The auditory and visual display for the condition with no ACC was the same as the auditory and visual FCW display in the ACC with FCW condition. The visual display was a high, heads-down display consisting of an icon showing a collision between two cars from the driver's perspective; it was triggered in the same manner as in previous studies (NHTSA, 2005). The warning is triggered when the distance and closing velocity combine to create a situation in which a collision will occur if drivers fail to brake heavily. Algorithm makes this assessment according to an assumed deceleration and reaction time of the driver. The auditory warning was a tone similar to the warning used in previous studies (Lee, McGehee, Brown, & Reyes, 2002; Tan & Lerner, 1995). The volume of this auditory alert was 80 dBA, approximately 10 dB above the ambient noise of the vehicle and one cycle of the tone lasted for 2.1 s. The haptic seat was a standard automotive seat modified to include 24 vibrating actuators, similar to ones used in previous studies (Lee, Hayes, Wiese, & McGehee, 2002; Lee et al., 2004). The actuators were configured to deliver vibrations that started at the front of the seat and progressed to the rear. The progression took 2.25 s to complete and included a 500 ms pause without vibration at the end of the cycle. The brake pulse was a half sine wave with a peak magnitude of 0.015 g and lasted 400 ms. Each of these warnings was repeated if the conditions triggering the warning were still valid when the warning signal had completed its cycle.

The ACC system used for this study is described by VanderWerf et al. (2001), and provides for both free drive and interaction with other vehicles on the roadway. In free-drive mode, acceleration inputs were directly proportional to the difference between the current speed and the desired speed. When impeded by a slower-moving lead vehicle, the ACC used a linear model that adjusted acceleration according to the difference between actual and desired distance, as shown in the following equation:

$$acceleration(t) = \alpha(Distance\,(t) - TargetDistance)$$

Desired distance was determined based on the desired time gap and the current speed. The algorithm is also constrained to brake at no more than 0.25 g. In the moderate and severe events the ACC braked at approximately 0.25 g. The onset of this braking occurred approximately 300 ms after the event onset, simulating sensor and algorithm latencies that are present in actual ACC systems. The onset of the ACC braking provided drivers with an additional cue regarding the possible need to intervene.

Simulator, Scenario, and Virtual Environment

The National Advanced Driving Simulator (NADS) was used for this experiment. This simulator includes a 360 by 40-degree view and a motion base capable of replicating sustained accelerations of 0.6 g and vibrations of from 3 to 40 Hz. A sound system provides three-dimensional auditory cues that include wind and road noise, as well as the sound of other vehicles. The experiment was conducted with a 1996 Chevrolet Malibu cab. The NADS Dyna dynamics model paired with the motion base provided participants with realistic acceleration cues associated with manual and ACC braking. The motion base generated longitudinal acceleration cues that matched those specified by the simulation of the vehicle dynamics. Specifically, if the driver pressed the brake and decelerated at 0.4 g, the motion base produced acceleration cues of 0.4 g—a 1:1 scaling of acceleration. During extreme braking there was nonlinear scaling to ensure that commanded decelerations remained within the limits of the motion base, which allowed approximately 0.6 g of sustained deceleration. Lateral and vertical scaling were set at 0.5 to accommodate the effects of the curves and leave the motion base maximum flexibility in generating longitudinal acceleration cues.

Both practice and experimental drives were conducted on a rural freeway with two lanes of traffic in each direction and with a posted speed limit of 65 mph (105 kph). Traffic density was 18-35 vehicles/lane/mile. The headway between vehicles varied between 1.2 and 2.6 seconds. This corresponds to level of service where the traffic was relatively free-flowing, but there was some influence of other vehicles (TRB, 2000). Drivers were instructed to stay in the right lane and follow the vehicle ahead. A car in the left lane shadowed the driver to discourage lane changes.

The distraction tasks were triggered at preset locations along the route. Once triggered, an audio message was played instructing the participant to press a button on the lower right of the center stack/consol and to watch a co-located digital display. The button press caused the display to show a random sequence of digits at the rate of 4 Hz. The driver's task was to count the number of times the numeral "4" appeared. This visually demanding distraction occurred 62 times during the drive. The mean time between occurrences was 30.4 seconds, with a standard deviation of 15.4 seconds. Participants were told to drive normally and to attend to the non-driving task as they might in a real driving situation.

The button press associated with the distraction task also initiated the events described in Table 1. Drivers experienced 14 events that required an ACC or manual braking response, and so these events occurred approximately 22.6 percent (14/62) of the time the button was pressed. The frequency with which moderate and severe events coincided with the button press was only 9.7 percent (6/62). Linking the event onset with the button press ensured that the driver was at least moderately distracted at the onset of the braking event.

Procedure

Participants listened to a description of the experiment and then consented to participate. They then completed a demographic questionnaire that assessed driving habits. The experimenter described the details of the study and provided a paper copy and recorded description of the in-vehicle technology they would experience. The participant could ask questions at any time. The number-counting activity was also described.

The participants were then escorted into the simulator where they received specific instructions regarding the simulator cab. They began with a short practice drive of approximately 6 minutes. During the practice drive, they familiarized themselves with the vehicle and its handling characteristics and were reminded of how to use the ACC and FCW systems. The practice drive included examples of braking lead vehicle and activation of the warning system. After the practice drive, the participants completed another Workload/Trust survey.

During the main drive the participants drove along a rural highway for approximately 35 minutes. After completing the main drive, each participant completed a Workload/Trust survey (Bisantz & Seong, 2001; Hart & Staveland, 1988; Rotter, 1967) and a Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993). The participant was then escorted from the simulator, debriefed, completed a simulator realism questionnaire and payment forms, and was escorted from the building.

RESULTS

All analyses were performed using SAS General Linear Model (GLM), with a criterion of statistical significance of $p < 0.05$. For all post-hoc evaluations, the Waller-Duncan k-ratio t-test was used to maximize the ability to find differences present in the data while providing more control for type I error than the standard t-test. Only four crashes occurred and the crashes were not concentrated in any particular condition, so crash data were not included in the analysis.

The first analysis excluded inappropriate responses of the ACC and FCW and included only those events described by the first six rows of Table 1. As there were different numbers of occurrences during the drive for the mild, moderate, and severe events, means were calculated for each event severity and each event type. The value analyzed for the mild events represented the mean of 4 mild events, the value for the moderate events represented the mean of 2 events, and the value for the severe events was the actual measure for the severe event. The variables for the GLM model for this analysis included ACC conditions, event severity, event type, and gender.

The ACC alert modalities, along with event severity, event type, and their interactions influenced the minimum time to collision (TTC). Not surprisingly, more severe events were associated with smaller minimum TTC, $F(2, 100)=5467.04$, $p<.001$. The revealed lead vehicle situations also led to much smaller minimum TTC compared to the braking lead vehicle events, $F(2, 100)=5734.22$, $p<.001$. More interesting is the effect of the presence of the ACC system. Figure 3 shows that drivers with ACC had larger minimum TTC during the mild and moderate severity braking lead vehicle. Importantly, the scale differs substantially in these two figures. The minimum TTC is generally much shorter in the revealed lead vehicle events (Figure 2) than in the braking lead vehicle events (Figure 3). For the moderate lead vehicle braking situation, the post-hoc tests show that no ACC condition has a significantly shorter minimum TTC and that the brake pulse cue leads to a significantly greater minimum TTC (5.88 s) compared to the auditory cue (5.57 s). There were no significant differences for warning modality in the moderate revealed lead vehicle conditions, although there was a trend favoring the brake pulse similar to the braking lead vehicle condition. Considering only severe events, neither the modality of the alert, nor the presence of ACC had a statistically significant effect on the minimum TTC, $F(4, 40)=0.26$, $p>0.05$.

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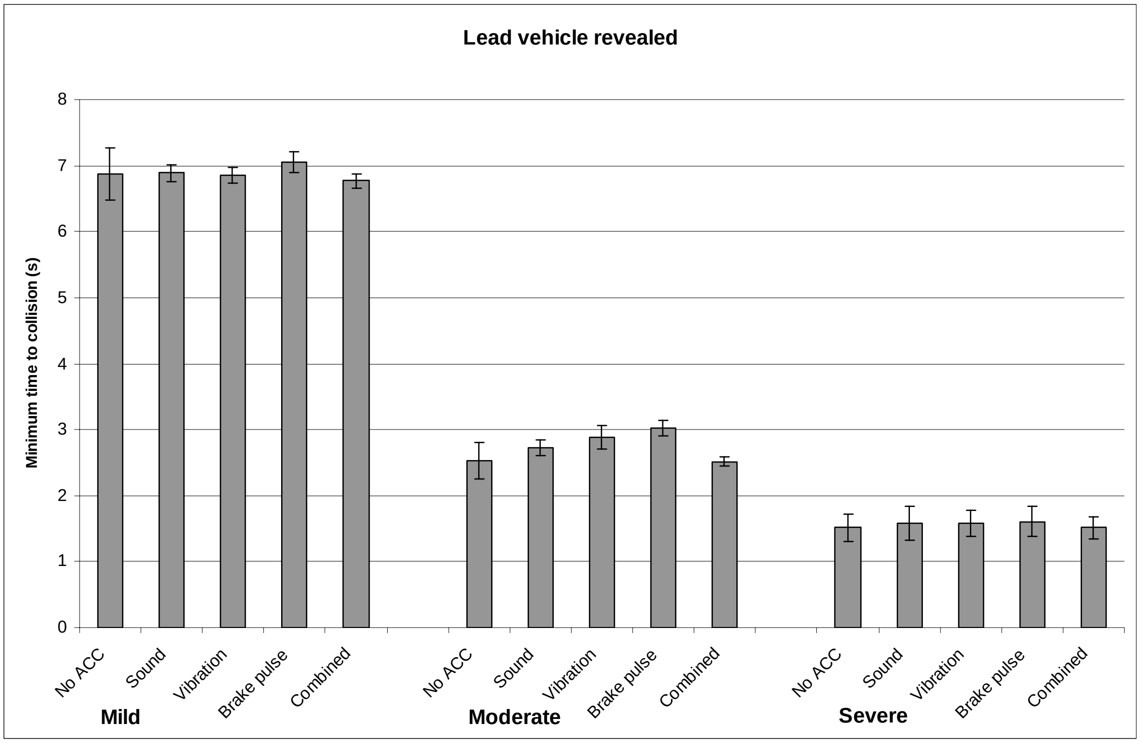

Figure 2. Minimum time-to-collision as a function of ACC alert modality and event severity in the revealed lead vehicle scenario. The No ACC condition included the sound and visual warning. The No ACC included the sound and visual warning, and all conditions included a visual warning.

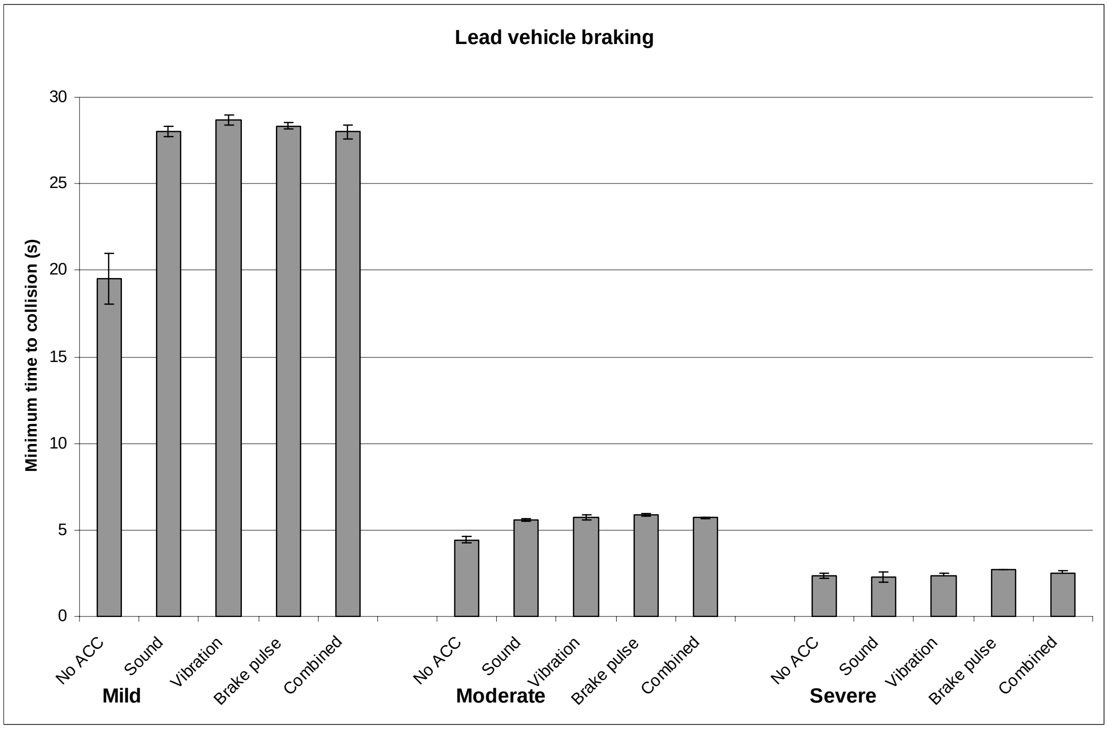

Figure 3. Minimum time-to-collision as a function of ACC alert modality and event severity in the braking lead vehicle scenario.

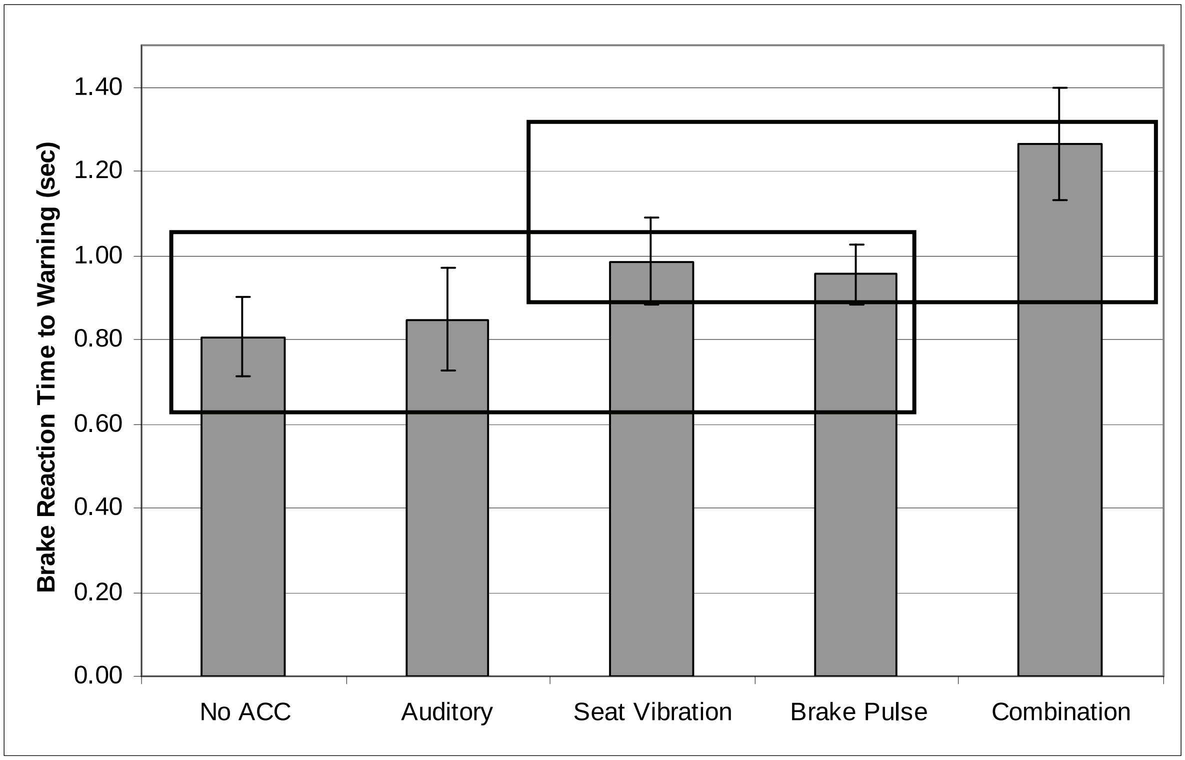

Figure 4. The brake reaction time as a function of warning modality. All conditions included a visual alert and the "No ACC" condition had an auditory and visual alert. All responses are to severe events. The boxes indicate statistically significant differences.

Although the minimum TTC during severe events was similar for all ACC alert modalities, the brake reaction time was substantially slower for those drivers with the combined auditory, seat vibration, and brake pulse warning, for both the lead vehicle revealed and braking condition $F(4,50)=2.91$, $p<0.05$. Brake reaction time is defined by the time from the warning onset to the initial depression of the brake pedal. Post hoc tests showed that the combination of cues resulted in a slower response than did the no ACC and auditory warning conditions. The auditory and visual alerts, shown in the leftmost columns in Figure 4, resulted in the fastest response, which did not depend on whether drivers had ACC or not. Drivers responded to the warnings for the revealed lead vehicle events faster (0.58 s) than they did to the braking lead vehicle events (1.23 s) or to the inappropriate warnings (1.22), $F(2,49)=33.4$, $p<.0001$.

The alert modality had no significant effect on driver reaction to inappropriate responses of the ACC and FCW. A detailed analysis of video recordings of drivers' foot movements showed that neither the degree to which the foot hovered over the brake, $F(4,100)=0.60$, $p>.05$, nor the frequency with which drivers depressed the brake, $F(4,100)=0.56$, $p>.05$, was related to alert modality. The feet of most drivers (78.3%) moved or hovered over the brake in response to the inappropriate collision warning, but only 56.6 percent actually depressed the brake. Similarly, the maximum braking of drivers in all alert modality conditions was similar, $F(4, 50)=0.45$, $p>.05$.

The presence of ACC did not affect engagement with the secondary task, as measured by the amount of time drivers looked at the secondary task display from the onset of the instruction to begin the task to the time the button was pressed, $F(4, 55)=1.1, p>.05$, or for the 3 seconds following the button press, $F(4, 81)=1.81, p>.05$. Overall, drivers kept their eyes on the road for approximately 68 percent of the 3 seconds following the button press, independent of whether they had ACC and independent of the alert modality, $F(4,88)=0.40, p>.05$.

The mild and moderate events did compel some of the drivers to respond by either moving their foot or applying the brake pedal, even though these responses were not necessary for drivers with ACC. On average, drivers responded to 10 percent of the mild events, 45 percent of the moderate events, and 95 percent of the severe events. Although ACC could accommodate the mild and moderate events, the rate of response for drivers with ACC was approximately the same as for drivers without ACC.

DISCUSSION

ACC helped drivers maintain a larger safety margin, as measured by the minimum TTC, during mild and moderate braking lead vehicle events. Because ACC helped maintain a larger safety margin during the less severe braking events, it may have important indirect benefits, affecting other drivers and the overall traffic flow rather than the likelihood of a crash for the driver using it. An important overall safety benefit of ACC may be its ability to dampen disruptions in traffic flow by maintaining a more consistent TTC in the face of small disturbances. Small disturbances can transform free-flowing traffic into congestion and create severe braking situations that can endanger drivers (Kerner, 2000, 2002). This study complements previous traffic simulation studies and shows how ACC might dampen disruptions associated with braking lead vehicles and abrupt lane changes. The benefit of this potential effect of ACC on traffic flow stability would be considerable (Li & Shrivastava, 2002), and has the potential to reduce the number of hazardous lane changes and even decrease pollution levels (Ioannou & Stefanovic, 2005).

ACC resulted in a larger and more consistent minimum TTC primarily in the mild and moderate braking lead vehicle events. One explanation is that the visual information available to drivers during the braking lead vehicle situations—the increasing visual angle of the lead vehicle—is a much less salient cue compared to the abrupt onset of a threat that occurs when the lead vehicle changes lanes (Hoffmann & Mortimer, 1996). Because ACC begins to respond immediately to dangers drivers may not appreciate, ACC might provide a particularly large safety benefit in braking lead vehicle situations.

Contrary to previous studies (Stanton & Young, 1998), ACC did not degrade safety during severe braking events. During the severe braking situations, drivers did not respond more slowly when using ACC, except when they received alerts that included auditory, seat vibration and brake pulse cues, and the minimum TTC was similar for those with and without ACC. In addition, neither the use of ACC nor the modality of the warnings affected drivers' response to collision warnings. Drivers using ACC do not seem more prone to responding to inappropriate warnings. One explanation for the benefit of ACC is that it augmented drivers' responses by initiating a braking response approximately 0.5 to 1.5 seconds before the warning onset and by continuing the response until the driver responded. The braking response of the ACC and the associated deceleration cues may be critical in re-engaging the driver in the control process. Studies in fixed-base driving simulators do not provide these deceleration cues and may overestimate the difficulty drivers might have in re-engaging and responding to critical braking events. Future research should assess the degree to which the profile of the onset of ACC braking influences driver response to critical situations.

The apparent benefit of the ACC here contrasts with other studies that have shown a performance decrement with such systems (Stanton & Young, 1998). One explanation for this difference is that drivers in this study received warnings for all the braking events to which a response was required. In other studies, the ACC failed without warning. This study focused on situations that exceeded the braking authority of the ACC, which contrasts with other studies that considered the effect of sensor failures. As an example, in one study over 25 percent of drivers failed to intervene when a sensor failure caused the ACC to accelerate into a car ahead (Stanton & Young, 1998). These results point to two distinct failure modes that merit attention in ACC evaluation. The first represents limits of ACC braking authority for which appropriate alerts have been developed. This study shows that even distracted drivers can resume control effectively if they are alerted to the inability of the ACC to accommodate an evolving traffic situation. The second failure mode represents unexpected failures for which alerts are not typically provided (Stanton & Young, 1998). Drivers respond poorly to these situations, often failing to intervene in a timely manner. Such failures occur rarely, and may be underrepresented in field tests because field-test vehicles tend to be new, well maintained, and less prone to sensor failures. Future research assessing the benefit of providing drivers with real-time information regarding sensor performance may be critical to avoiding this second failure mode, which seems to be a particularly potent threat to driving safety.

Another possible risk associated with ACC is that automating parts of the driving task will lead drivers to engage in more distracting tasks and to engage in those tasks more frequently. Given the explicit instructions governing engagement in the secondary task in this experiment, it is perhaps not surprising that this study found no evidence of such behavior. Engagement in distracting activities can be considered at the strategic, tactical, and operational levels of behavior (Lee & Strayer, 2004; Poysti, Rajalin, & Summala, 2005). The tactical level describes drivers' decision to engage in a potentially distracting activity. The operational level describes the micro-structure of how drivers divide their attention between driving and the secondary task. This study provides no insight into tactical behavior because participants were instructed to engage in the secondary task at specific times. However, the experiment did leave drivers with some degree of flexibility at the operational level as to how they responded to the secondary task. Drivers with ACC did not look away from the road any more frequently than drivers without ACC, nor did they engage the secondary task more rapidly. This result is consistent with recent field data that showed drivers did not increase the frequency with which they engaged in secondary tasks when they began using an ACC-equipped vehicle (Sayer, Mefford, & Shirkey, 2005). It must be noted, however, that the field study data reflect behavior for only three weeks and the current study reflects behavior for only 35 minutes; longer exposure may be more likely to induce behavioral adaptation. Behavioral adaptation may also be more likely with tasks that have a less obvious potential to distract. The distraction in this experiment involved a visually demanding task that drivers likely perceived as distracting. Drivers may not recognize the consequences of distractions that involve primarily cognitive demands (Strayer, Drews, & Johnston, 2003), and it may be that drivers would be more willing to perform these tasks with

ACC. The degree to which ACC induces behavioral adaptation may also depend on the latitude in task performance. The one used in this study provided relatively little latitude, but there are many tasks that drivers could engage in to a greater or lesser degree. Such a situation led to behavioral adaptation with drivers using ACC on a test track (Rudin-Brown & Parker, 2004). Future research should define the boundary conditions that induce behavioral adaptation with ACC.

In generalizing the results of this study, it is important to consider that drivers were exposed to a relatively large number of events. However, only 2 of them required a response in the ACC condition, and so presented drivers with a substantial degree of surprise. Since these events were always triggered when the driver initiated the distraction task, drivers may have associated the distraction task with traffic events. However, the majority of the distraction tasks were not associated with an event. As a result, drivers did not prepare to brake every time they pressed the button—90 percent of the drivers did not respond to mild events, even with only a slight foot movement. If drivers were cued by the secondary task to expect a lead vehicle change, this number would have been much higher. At the same time, drivers were faced with an active driving environment that tended to keep them engaged in the driving task. Drivers with ACC responded to events that could have been accommodated by ACC with a similar frequency as those without ACC, suggesting that drivers carefully monitored the ACC performance. Future research might consider measures of trust and reliance that might illuminate the cause of the frequent and rapid responses of drivers to the events seen in this experiment. Fewer events and more experience with ACC might have led to disengagement with the driving task, making it more difficult for drivers to re-enter the control loop. At the same time, fewer events may have led to a greater degree of surprise for drivers with and without ACC, and in such a situation the benefit of ACC/FCW may have been greater. Another challenge in generalizing these results is the degree to which the specific ACC/FCW characteristics affect driver response. ACC systems differ with respect to control algorithm and maximum braking and could lead to more or less driver engagement and correspondingly longer or shorter reaction times in response to roadway events. These differences might have important effects on how well the ACC/FCW is able to enhance driving safety. Further research is needed to explore how drivers respond to situations of greater disengagement from the task of driving and of greater surprise.

Substantial research has demonstrated the benefit of using redundant sensory channels to convey information (Nickerson, 1973; Todd, 1912). As an example, responses to a combined visual, auditory, and tactile stimulus were faster than to stimuli composed of two modalities, which were faster than responses to single-modality stimuli (Diederich & Colonius, 2004). Similarly, adding visual cues to an auditory warning enhanced drivers' responses (Belz, Robinson, & Casali, 1999). This redundancy gain suggests the combination of auditory, seat vibration, visual, and brake pulse would support the fastest response in the current study; however, this did not prove to be the case. Response to the multimodal combination was over 400 ms slower than the auditory and visual alert. This result is not unique. In the context of human-computer interaction, feedback that combined auditory, haptic, and visual information performed worse than did the bimodal combination of visual and haptic (Vitense & Jacko, 2003). In the context of patient monitoring, a redundant combination of auditory and visual information resulted in poorer performance than either auditory or visual alone (Seagull, Wickens, & Loeb, 2001). Drivers' response to a lane departure collision warning had a similar effect, where the multimodal warning also resulted in slower responses (Tijerina, Jackson, Pomerleau, Romano, & Petersen, 1996). Although generally beneficial, redundancy gain is thus not universal. One possible explanation is that multi-modal warnings can either be perceived as a single cue or as a set of cues. When perceived as a single cue, performance may be enhanced, while performance degrades when a multi-modal warning is perceived as multiple cues. Understanding how multi-modal warnings can capitalize on cross-modal inattention may benefit from recent findings in neuropsychology (Driver & Spence, 1998; Spence, 2002). Matching the time and frequency profiles may help create a single-cue Gestalt that can be processed quickly by the driver. Effective communication between the ACC and the driver may depend on identifying the characteristics of multi-modal signals that must be matched to form such a Gestalt.

Beyond the combination of auditory, seat vibration, brake pulse, and visual cues, the various alert modalities performed similarly when considered independently. The slightly greater minimum time to collision associated with the brake pulse in the moderately severe situations may reflect a benefit of the ACC deceleration reinforcing the brake pulse warning. To the extent that this effect depends on stimulus-response compatibility, the benefits of brake pulse cues will likely increase as an increasing number of collision warning systems enter the vehicle. Further research should identify situations in which non-traditional warning modes might have more pronounced benefits, such as when drivers are faced with warnings from several systems.

APPENDIX A: SIMULATION SCENARIOS AND DRIVING EVENTS

The following tables and figures document the specific sequence of events experienced by the drivers. Each driver experienced one of the two drive scenarios composed of the specified sequence of events. The major difference between the scenarios is that in one the severe braking lead vehicle event occurred first and in the second the severe revealed lead vehicle event occurred first.

Table A1. Order of events in the two experimental drives.

Event	**Order 1**	**Order 2**
1st	Mild Revealed Lead Vehicle	Mild Braking Lead Vehicle
2nd	Mild Braking Lead Vehicle	Moderate Revealed Lead Vehicle
3rd	Moderate Braking Lead Vehicle	Mild Inappropriate Response
4th	Mild Inappropriate Response	Mild Braking Lead Vehicle
5th	Severe Braking Lead Vehicle	Moderate Inappropriate Response
6th	Mild Revealed Lead Vehicle	Severe Revealed Lead Vehicle
7th	Moderate Revealed Lead Vehicle	Mild Inappropriate Response
8th	Mild Inappropriate Response	Mild Revealed Lead Vehicle
9th	Mild Braking Lead Vehicle	Moderate Braking Lead Vehicle
10th	Moderate Inappropriate Response	Mild Braking Lead Vehicle
11th	Mild Revealed Lead Vehicle	Mild Revealed Lead Vehicle
12th	Severe Inappropriate Response	Severe Inappropriate Response
13th	Mild Inappropriate Response	Mild Inappropriate Response
14th	Mild Revealed Lead Vehicle	Moderate Braking Lead Vehicle
15th	Moderate Braking Lead Vehicle	Mild Revealed Lead Vehicle
16th	Mild Braking Lead Vehicle	Mild Braking Lead Vehicle
17th	Moderate Inappropriate Response	Moderate Revealed Lead Vehicle
18th	Mild Braking Lead Vehicle	Moderate Inappropriate Response
19th	Moderate Revealed Lead Vehicle	Mild Revealed Lead Vehicle
20th	Mild Inappropriate Response	Mild Inappropriate Response
21th	Final	Final

Tables A2 and A3 place the driving events of Table A1 in the context of the distraction task; Figures A1 and A2 show how these events were situated on the route the participants drove. The participant experienced an audio cue (AC) periodically such that the mean time between audio cues was approximately 30.4 seconds, with a standard deviation of 15.4 seconds. The auditory cue asked the participant to initiate the distraction task. Participants pressed a button on the display to initiate the distraction task and this button press also initiated the lead vehicle braking and lead vehicle revealed events in Table A2 and A3. Figure A.1 and A2 show a map of the visual database with the approximate location of each event. The drive ended with the driver exiting the freeway and following a lead vehicle to a stop.

Table A2. Events for Order 1. AC signifies the auditory cue, R represents the lead vehicle revealed, and B represents the lead vehicle braking events.

Event	Event Name	Distance From Last Audio Cue (feet)	Time From Last Audio Cue (seconds @ 65mph)
	AC		
1	Mild R	2500	26
	AC	3800	40
2	Mild B	1600	17
	AC	4000	42
3	Mod B	1700	18
	AC	4200	44
	AC	1800	19
4	Mild FA	1500	16
	AC	4000	42
5	Severe B	2000	21
	AC	4000	42
	AC	3000	31
6	Mild R	1740	18
7	Mod R	5950	62
	AC	4310	45
	AC	1500	16
8	Mild FA	1800	19
	AC	4700	49
	AC	1500	16
9	Mild B	4500	47
10	Mod FA	4700	49
	AC	5000	52
	AC	1300	14
	AC	5000	52
	AC	1400	15
	AC	1400	15
	AC	3900	41
	AC	1400	15
	AC	1400	15
11	Mild R	3800	40
	AC	3700	39
12	Severe FA	2000	21
13	Mild FA	4500	47
	AC	2300	24
	AC	1000	10
14	Mild R	1342	14
	AC	5158	54
	AC	1300	14
	AC	1400	15
15	Mod B	1500	16
	AC	4500	47
16	Mild B	1300	14
	AC	4200	44
	AC	2500	26
17	Mod FA	3500	37
	AC	5000	52
18	Mild B	1100	12
	AC	4900	51
	AC	1100	12
	AC	1400	15
	AC	4500	47
	AC	4500	47
	AC	1000	10
	AC	2000	21
	AC	5000	52
19	Mod R	3700	39
	AC	4300	45
20	Mild FA	1300	14
	AC	2700	28
	AC	2000	21
21	Severe R	3000	31

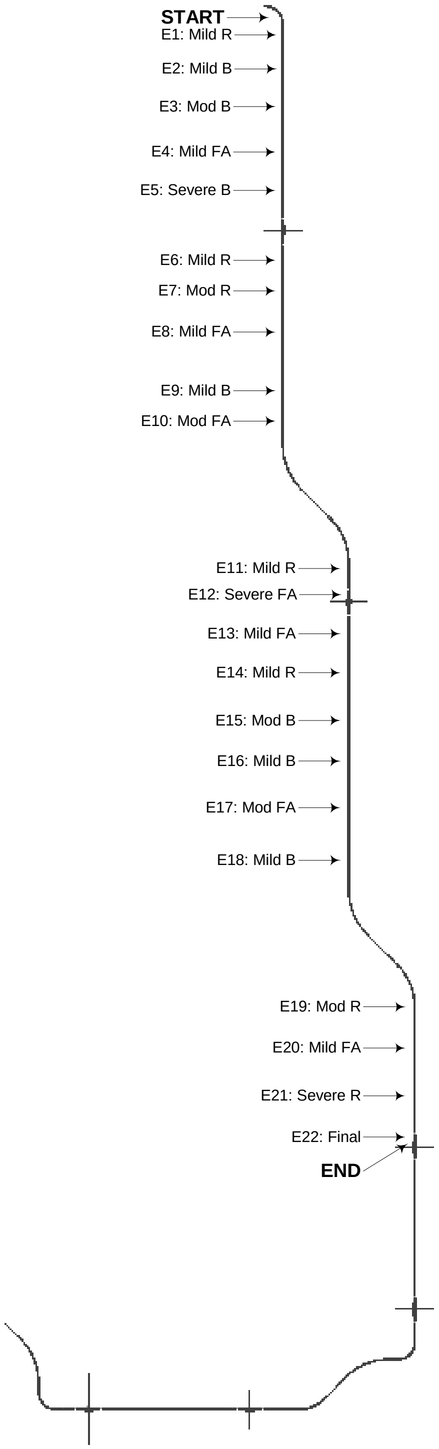

Figure A.1. Map of roadway for the drive for Order 1. FA indicates a false alarm or inappropriate response of the ACC and FCW.

The order of events for the second of the two experimental drives is shown in Table A3. Figure A2 shows a map of the visual database with the approximate location of each event. The participant experienced an audio cue (AC) periodically such that the mean time between audio cues was approximately 30.5 seconds with a standard deviation of 16.3 seconds.

Table A3. Events for Order 2. AC signifies the auditory cue, R represents the lead vehicle revealed, and B represents the lead vehicle braking events.

Braking event	Event Name	Distance From Last Audio Cue (feet)	Time From Last Audio Cue (seconds @ 65mph)
	FA		
1	Mild B	2900	30
	FA	4400	46
2	Mod R	2000	21
	FA	4600	48
3	Mod FA	1200	13
	FA	2700	28
	FA	1800	19
4	Mild B	1500	16
	FA	4500	47
5	Mod FA	2500	26
	FA	3000	31
	FA	3000	31
6	Severe R	1740	18
7	Mod FA	6450	68
	FA	2310	24
	FA	1000	10
8	Mild R	1700	18
	FA	6800	71
	FA	1500	16
9	Mod B	2500	26
10	Mild B	5000	52
	FA	5000	52
	FA	3000	31
	FA	5000	52
	FA	1400	15
	FA	1400	15
	FA	3900	41
	FA	1400	15
	FA	1400	15
11	Mild R	4100	43
	FA	3400	36
12	Severe FA	2000	21
13	Mild FA	4500	47
	FA	2500	26
	FA	1500	16
14	Mod B	1200	13
	FA	4100	43
	FA	1200	13
	FA	1500	16
15	Mild R	1442	15
	FA	5058	53
16	Mild B	1300	14
	FA	4200	44
	FA	2500	26
17	Mod R	2442	26
	FA	6058	64
18	Mod FA	1100	12
	FA	4900	51
	FA	1100	12
	FA	1400	15
	FA	4500	47
	FA	4500	47
	FA	1000	10
	FA	2000	21
	FA	5000	52
19	Mod R	3700	39
	FA	4300	45
20	Mild FA	1300	14
	FA	2700	28
	FA	2000	21
21	Severe B	3000	31

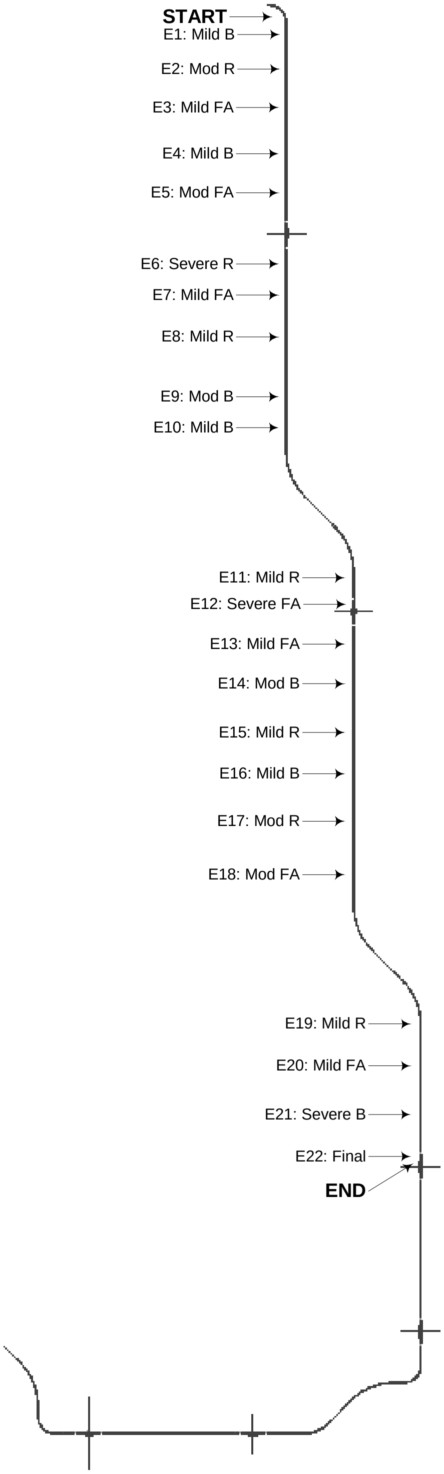

Figure A2. Map of roadway for the drive for Order 2.

APPENDIX B: PARTICIPANT INSTRUCTIONS AND PROTOCOL

For participants with ACC

CAB ORIENTATION *(in dome, outside cab)* (For Active Warning & ACC systems only)

(open car door) **Before you get in, let me explain how to adjust the seat.**

The seat adjusts forward and backward with this lever *(point)*. **To adjust the back of the seat, use this lever** *(point)*. **The steering wheel adjusts up and down using this lever** *(point)*. **Please be seated. Please fasten your seat belt at this time and keep it fastened until we come back to the dock. The armrest must stay in the "up" position.**

(while participant is getting in, go around)(speaker "ON")(adjust eye tracker)

(Dome light out)(Control room takes 1st eye tracking photos)

As explained in the training session, you will be using the warning system and adaptive cruise control today. The light for the Warning System will appear here *(point)*. **To activate the Adaptive Cruise Control you will use the resume button** *(point)* **located on the steering column. For the number counting activity, you will use this button** *(point)*. **This is also where the numbers display is located.**

(control room calibrates eye tracker) (continue if control room is not ready for eye tracking calibration)

The outside mirrors on the left and right adjust using this panel of buttons *(point).***You can manually adjust the in-cab rearview mirror. The gear lever is in the center. You will shift into D for drive and P for park during this drive. The car's engine is already on.**

Do you have any questions?

(following cue from Simulator Operator that dome will begin moving)
The simulator will soon be moving towards its start position. During this process, you may hear rumbling sounds and feel vibrations. This is normal.

There are microphones in the car so the Simulator Operators can hear us at all times. If for any reason, you want to stop driving, please let us know. The Operators will hear you; they will be able to bring us to a stop in just a few seconds.
(adjust cameras, lights down in dome)

(after 1st eye tracking photos)

FAMILIARIZATION DRIVE

The first drive today is split into four segments. The first segment will familiarize you with driving in the simulator. The second segment will familiarize you with interacting with other vehicles. The third segment will allow you to experience the warning. The fourth segments will familiarize you with interacting with the adaptive cruise control. You will be given instructions about each segment as it begins.

Throughout the drive you will be performing the number counting activity. When asked please press the button and report the number of times that the number "4" appears.

The drive will begin with your vehicle parked in the right lane of an open roadway. When told to begin, shift into drive and accelerate to 65 mph.

Do you have any questions? *[Wait for pupil calibration] (speaker "OFF")*

(wait for cue from simulator operator that the system is ready)

(questions) **Are you ready to drive?**

(cue from Simulator Operator) (Run)

Please press the brake, shift into Drive and accelerate to 65 mph. Stay in the right lane for the remainder of the drive.

(cue from Control Room)(once at 65 mph and white vehicle passes)

Segment 1) To become familiar with the handling of the vehicle during this segment you should press lightly on the brakes and steer within your lane.

(cue from Control Room, Lead vehicle moving into position)

Segment 2) During this segment you will interact with the vehicle in front of you as you normally would.

(cue from Control Room, after event 2)

Segment 3) The vehicle in front of you will soon begin slowing. To provide you a chance to experience the warning, do not slow or brake until the warning has activated.

(cue from control room, following warning light activation and lead vehicle accelerates)

Segment 4) Please accelerate to 65 mph and engage the Adaptive Cruise Control by pressing the resume button.

END OF FAMILIARIZATION DRIVE

(after the final braking event) **Please come to a complete stop and put the vehicle into park. The operator is now preparing the simulator for our main drive. I will now read the instructions for that drive.** *[Go to MAIN DRIVE]*

MAIN DRIVE

The main purpose of your drive today is to evaluate the realism of the simulator; therefore you should pay attention to your driving environment including the behavior of the vehicles within the driving environment. In addition, pay attention to the feel of the steering and braking system so

that you can help to evaluate the realism of the drive.

For this drive both the warning system and the Adaptive Cruise Control will be active. You will activate the ACC by pressing the resume button.

When the drive begins, your vehicle will be parked on the shoulder of an open roadway. Wait for 6 cars to go by and then merge into the right lane behind the "green" vehicle. Accelerate to 65 mph, and then engage the Adaptive Cruise Control. Remember that if you press the brake, the system will disengage. You will need to accelerate back to 65 mph then press the resume button again to engage it again.

During this drive you will be performing the number counting activity. When asked to do so please press the button and report the number of times the number "4" appears.

During your drive it is important that we have as little interaction as possible so that I don't interfere with your driving experience.

Do you have any questions before we begin?

(wait for cue from simulator operator that the system is ready)

(questions) **Are you ready to drive?**

(cue from Simulator Operator)(at run)

Press the brake, shift into Drive. Wait for the green vehicle to pass, then merge into the right lane, accelerate to 65mph then engage the ACC. Once you have pulled into the right lane remain there until the end of the drive.

(cue from simulator Operator) **Please exit the roadway using the exit ramp ahead**

END OF MAIN DRIVE *(go to stop sign on ramp)*

(cue: at STOP SIGN warning sign day--) **Please come to a complete stop at the stop sign. Put the vehicle into park and leave your seatbelt fastened as we go to the dock. I have some questionnaires for you to fill out while we are waiting.** *(administer Workload Trust Questionnaire and SSQ)* **If you don't complete them in the car you may take them with you to one of our rooms.**

RESTART

When the drive begins again, your vehicle will be parked on the shoulder of an open roadway. Wait for 6 cars to go by and then merge into the right lane, accelerate to 65 mph, and engage the Adaptive Cruise Control. Remember that if you press the brake, the system will disengage and you will need to accelerate back to 65 mph and press the button again to reengage.

Do you have any questions before we begin?
(wait for cue from simulator operator that the system is ready)
(questions) **Are you ready to drive?**
(cue from Simulator Operator)
After the group of vehicles goes by, press the brake and shift into Drive then merge into the right lane, accelerate to 65mph, and engage the Adaptive Cruise Control. As before, you will remain in the right lane until the end of the drive.
(cue from simulator Operator) **Please exit the roadway using the exit ramp ahead.**
(go to END OF MAIN DRIVE)

For Participants without ACC

CAB ORIENTATION *(in dome, outside cab)* (For Active Warning & ACC systems only)
(open car door) **Before you get in, let me explain how to adjust the seat.**
The seat adjusts forward and backward with this lever *(point)*. **To adjust the back of the seat, use this lever** *(point)*. **The steering wheel adjusts up and down using this lever** *(point)*. **Please be seated. Please fasten your seat belt at this time and keep it fastened until we come back to the dock. The armrest must stay in the "up" position.**
(while participant is getting in, go around)(speaker "ON")(adjust eye tracker)
(Dome light out)(Control room takes 1st eye tracking photos)
As explained in the training session, you will be using the warning system today. The light for the Warning System will appear here *(point)*. **For the number counting activity, you will use this button** *(point)*. **This is also where the numbers display is located.**
(control room calibrates eye tracker) (continue if control room is not ready for eye tracking calibration)
The outside mirrors on the left and right adjust using this panel of buttons *(point).* **You can manually adjust the in-cab rearview mirror. The gear lever is in the center. You will shift into D for drive and P for park during this drive. The car's engine is already on.**
Do you have any questions?

(from back seat of cab) (after 1st face photos)
(following cue from Simulator Operator that dome will begin moving) **The simulator will soon be moving towards its start position. During this process, you may hear rumbling sounds and feel vibrations. This is normal.** **There are microphones in the car so the Simulator Operators can hear us at all times. If for any reason, you want to stop driving, please let us know. The Operators will hear you; they will be able to bring us to a stop in just a few seconds.** *(adjust cameras, lights down in dome)*

FAMILIARIZATION DRIVE

The first drive today is split into TWO segments. The first segment will familiarize you with driving the vehicle in the simulator. The second segment will familiarize you with interacting with other vehicles. The third segment will allow you to experience the warning. You will be given instructions about each segment as it begins.

Throughout the drive you will be performing the number counting activity. When asked please press the button and report the number of times that the number "4" appears.

The drive will begin with your vehicle parked in the right lane of an open roadway. When told to begin, shift into the drive and accelerate to 65 mph.

Do you have any questions? *[Wait for pupil calibration] (speaker "OFF")*

(wait for cue from simulator operator that the system is ready)

(questions) **Are you ready to drive?**

(cue from Simulator Operator) (Run)

Please press the brake, shift into Drive, and accelerate to 65 mph. Stay in the right lane for the remainder of the drive.

(cue from Control Room)(once at 65 mph and white vehicle passes)

Segment 1) To become familiar with the handling of the vehicle during this segment you should press lightly on the brakes and steer within your lane.

(cue from Control Room, Lead vehicle moving into position)

Segment 2) During this segment you will interact with the vehicle in front of you as you normally would.

(cue from Control Room, after event 2)

Segment 3) The vehicle in front of you will soon begin slowing. To provide you a chance to experience the warning, do not slow or brake until the warning has activated.

(following warning light activation and lead vehicle accelerates)

Please accelerate to 65 mph.

END OF FAMILIARIZATION DRIVE

(after the final braking event) **Please come to a complete stop and put the vehicle into park. The operator is now preparing the simulator for our main drive. I will now read the instructions for that drive.** *[Go to MAIN DRIVE]*

MAIN DRIVE

The main purpose of your drive today is to evaluate the realism of the simulator; therefore you should pay attention to your driving environment including the behavior of the vehicles within the driving environment. In addition, pay attention to the feel of the steering and braking system so that you can help to evaluate the realism of the drive.

For this drive the warning system will be active.

When the drive begins, your vehicle will be parked on the shoulder of an open roadway. Wait for 6 cars to go by and then merge into the right lane behind the “green” vehicle, accelerate to 65 mph. Remember that if you press the brake, you will need to accelerate back to 65 mph.

During this drive you will be performing the number counting activity. When asked to do so please press the button and report the number of times the number “4” appears.

During your drive it is important that we have as little interaction as possible so that I don’t interfere with your driving experience.

Do you have any questions before we begin?

(wait for cue from simulator operator that the system is ready)

(questions) **Are you ready to drive?**

(cue from Simulator Operator)(at run)

Press the brake and shift into Drive. Wait for the “green” vehicle to pass, then merge into the right lane, accelerate to 65mph. Once you have pulled into the right lane you will remain there until the end of the drive.

(cue from simulator Operator) **Please exit the roadway using the exit ramp ahead**

END OF MAIN DRIVE *(go to stop sign on ramp)*

(cue: at STOP SIGN warning sign day--) **Please come to a complete stop at the stop sign. Put the vehicle into park and leave your seatbelt fastened as we go to the dock. I have some questionnaires for you to fill out while we are waiting.** *(administer Workload Trust Questionnaire and SSQ)* **If you don’t complete them in the car you may take them with you to one of our rooms.**

RESTART

When the drive begins again, your vehicle will be parked on the shoulder of an open roadway. Wait for 6 cars to go by and then merge into the right lane, accelerate to 65 mph. Remember that if you press the brake, you will need to accelerate back to 65 mph.

Do you have any questions before we begin?

(wait for cue from simulator operator that the system is ready)

(questions) **Are you ready to drive?**

(cue from Simulator Operator)

After the group of vehicles goes by, press the brake and shift into Drive then merge into the right lane, accelerate to 65mph. As before, you will remain in the right lane until the end of the drive.
(cue from simulator Operator) **Please exit the roadway using the exit ramp ahead.**
(go to END OF MAIN DRIVE)

APPENDIX C: FOOT MOVEMENT ANALYSIS

In order to determine driver response during the ACC operation, we conducted a frame-by-frame analysis of foot movements during the lead vehicle braking and revealed scenarios. Normally, sensors in the accelerator pedal and brake pedal reliably and accurately provide driver response data automatically; however, with ACC or conventional cruise control, the only way to examine driver response is to examine the video manually. Using Noldus Observer software, we developed a method to decompose driver response during lead vehicle events.

Camera Views

Four cameras inside the vehicle continuously recorded: (1) head and eye movements, (2) body position and performance of a secondary task, (3) foot position, and (4) the forward view out the windshield (see Figure C1). While all camera views were visible to the analyst throughout the entire drive, the focus was solely on the third camera, which captured position of the feet in the foot well.

Figure C1. The views from the cameras inside the vehicle.

Determining Foot Positions

In order to determine and code the position of the foot, a 5” x 5” grid overlay was placed over the portion of the screen displaying the foot movement (see Figure C2). The overlay was numbered 11-99 and separated the screen into small enough sections to indicate a particular location. Analysts were to locate and code the resting position of the most northerly point of the shoe. For example, in Figure C2 below, the resting position would be coded as 53. In instances where the top of the shoe was outside the view of the video camera, the topmost cell was coded.

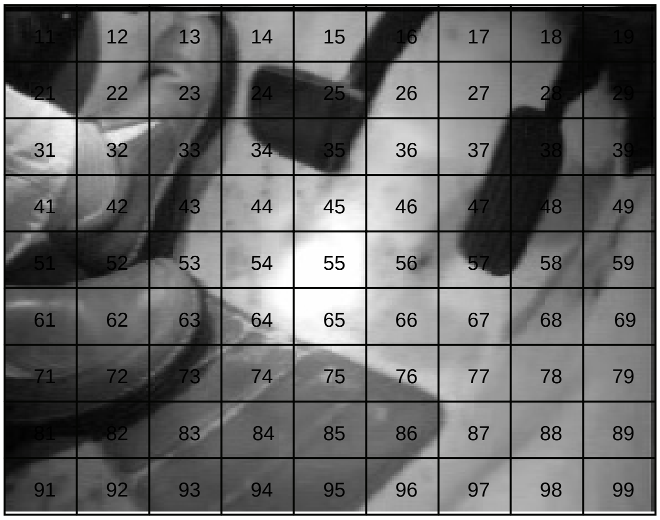

Figure C2. Grid overlay used to indicate position of the foot.

Foot positions were coded at the beginning of each event in order to capture the initial resting position of the foot. The other instance in which foot positions were coded was when the participant rested their foot on the floorboard, either, a) in between actions, or b) after the action had occurred and the event was over. This was done in order to determine the duration of the last action.

Foot Behaviors

The foot behaviors coded were:

- The first movement (twitch) of the foot that leads to an action (i.e., brake or accelerator press). Initial movements were coded as 101 and subsequent movements as 102, 103…. These were coded at the moment the foot started to leave its resting position.

- A hover over the brake pedal. The initial hover was coded as 201 with subsequent hovers as 202, 203…. These were coded when the foot was located over the brake pedal and stayed in this position for more than 5 frames.

- A brake press. The initial brake press was coded as 301 and subsequent presses as 302, 303…. These were coded at the instant the brake pedal was depressed. The amount it was depressed was not considered during this portion of the analysis.

- An accelerator hover. The initial accelerator hover was coded as 401 with subsequent hovers as 402, 403…. Accelerator hovers were coded only if the driver moved from the resting position directly to the accelerator and/or alternated between the accelerator and brake pedals. It was not coded if it was part of the normal braking behavior (i.e., driver applied brakes then accelerated after the event). Hovers were coded when the foot was located over the accelerator pedal and stayed in this position for more than 5 frames.

- An accelerator press. The initial accelerator press was coded as 501. Any subsequent presses were coded as 502, 503…. These were only coded in the same instances as mentioned above for accelerator hovers. Any amount of accelerator depression was considered a press.

- A hover at some location between the accelerator and brake pedal. The initial hover over an undefined position was coded as 601 with subsequent hovers as 602, 603…. Hovers were coded when the foot was located in this relative position for more than 5 frames. It should be noted that hovers did allow for some movement of the foot to occur, as long as it was not to one of the other positions defined in this section.

- Movement (twitch) of the foot that did not lead to an action (i.e., brake or accelerator press). That is to say, no action occurred during the entire event. Therefore, if a brake or accelerator press occurred at some time during the event, the 101 code described above was used.

Foot movements unrelated to the events (e.g., bouncing, stretching, moving to a new location) were not coded. In some instances this did require some subjectivity on the part of the analyst.

APPENDIX D: MINIMIMUM TTC DATA SUMMARY

Event Type	Event Severity	Condition	N	Mean	Std Dev	Std Error
Braking	Mild	No ACC	12	19.51	4.98	1.44
Braking	Mild	Sound	12	28.02	1.05	0.30
Braking	Mild	Vibration	12	28.67	0.96	0.28
Braking	Mild	Brake pulse	12	28.35	0.74	0.21
Braking	Mild	Combined	12	28.00	1.41	0.41
Braking	Moderate	No ACC	12	4.42	0.60	0.17
Braking	Moderate	Sound	12	5.57	0.14	0.04
Braking	Moderate	Vibration	12	5.69	0.51	0.15
Braking	Moderate	Brake pulse	12	5.89	0.30	0.09
Braking	Moderate	Combined	12	5.69	0.17	0.05
Braking	Severe	No ACC	12	2.35	0.58	0.17
Braking	Severe	Sound	12	2.27	0.94	0.27
Braking	Severe	Vibration	12	2.36	0.54	0.16
Braking	Severe	Brake pulse	12	2.68	0.15	0.04
Braking	Severe	Combined	12	2.51	0.58	0.17
Revealed	Mild	No ACC	12	6.87	1.40	0.40
Revealed	Mild	Sound	12	6.89	0.44	0.13
Revealed	Mild	Vibration	12	6.85	0.42	0.12
Revealed	Mild	Brake pulse	12	7.05	0.57	0.16
Revealed	Mild	Combined	12	6.77	0.35	0.10
Revealed	Moderate	No ACC	12	2.53	0.95	0.27
Revealed	Moderate	Sound	12	2.72	0.39	0.11
Revealed	Moderate	Vibration	12	2.88	0.60	0.17
Revealed	Moderate	Brake pulse	12	3.02	0.43	0.12
Revealed	Moderate	Combined	12	2.52	0.23	0.07
Revealed	Severe	No ACC	12	1.52	0.73	0.21
Revealed	Severe	Sound	12	1.58	0.88	0.25
Revealed	Severe	Vibration	12	1.58	0.70	0.20
Revealed	Severe	Brake pulse	12	1.61	0.81	0.23
Revealed	Severe	Combined	12	1.52	0.58	0.17

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DOT HS 810 981
August 2008

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