STATUS OF NHTSA'S REAR-END CRASH PREVENTION RESEARCH PROGRAM

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ABSTRACT

This paper provides an update on two cooperative research projects being conducted under the National Highway Traffic Safety Administration's (NHTSA) Rear-End Crash Prevention Program. The first project is the General Motors-Ford Crash Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) work. Since 1995, this project has been aimed at defining and developing pre-competitive enabling elements to facilitate FCW system deployment. The second project is the General Motors-led Automotive Collision Avoidance System Field Operational Test (ACAS FOT), which aims to accelerate the deployment of active safety systems by integrating and field-testing vehicles outfitted with Adaptive Cruise Control (ACC) and Forward Collision Warning (FCW) systems.

Results from the first CAMP FCW project played an important role in the development of the SAE J2400 Recommended Practice, "Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements". This paper discusses findings from the second CAMP FCW project, which was focused on evaluating and developing the FCW timing approach and examining drivers' decision-making and avoidance maneuver behavior in rear-end crash scenarios. The closed-course, test track methodology employed allows safely placing naive drivers in realistic rear-end crash scenarios so that driver behavior can be observed. The human factors experimentation and key results from this project will be discussed in this paper.

During the ACAS FOT project, a small fleet of vehicles was built and given to lay drivers for their personal use. Each driver had a vehicle for approximately four weeks, three of which had both the ACC and FCW features enabled. The collected data provided objective information about how the subjects used the system and its impact on their driving behavior. It also includes extensive subjective information collected through questionnaires, interviews, and focus groups. The system design, design and execution of the FOT, and highlights of results will be discussed in this paper.

INTRODUCTION

Forward Collision Warning (FCW) is an emerging automotive safety technology that provides alerts intended to assist drivers in avoiding rear-end crashes. NHTSA 2003 General Estimates System (GES) data indicate that rear-end crashes accounted for about 28% of the total 6,318,000 police-reported crashes in the United States. About 99.5% of these rear-end crashes involved at least one light vehicle (e.g., passenger vehicle, van and minivan, sport utility vehicle, and light truck).

NHTSA's rear-end crash prevention program began in 1991, when research to prevent rear-end crashes through the use of advanced technology was initiated under the U.S. Department of Transportation's (DOT) Intelligent Transportation System (ITS) Program. A brief history of NHTSA's rear-end crash prevention program is summarized below:

1991-1996: Rear-end crash problem definition, identification and assessment of potential countermeasure technologies (NHTSA-Volpe Center-Battelle-Calspan); development and use of a test bed system to develop performance specifications (Frontier Engineering); estimation of preliminary safety benefits (NHTSA-Volpe Center). Preliminary analysis of potential safety benefits showed that rear-end crash avoidance systems could prevent 48% of all rear-end crashes.

1997-2005: Cooperative research with CAMP (GM and Ford) to develop functional requirements, performance guidelines, and objective test procedures for rear-end crash avoidance systems on light vehicles. This activity involved human factors studies on closed-course test tracks to better understand how drivers respond to dynamic scenarios that lead to rear-end crashes. A follow-on research program studying alert algorithm timing and avoidance maneuvers for rear-end crash warning systems was also completed.

1999-2005: Cooperative agreement with General Motors and its partners Delphi Electronics, Hughes Research Labs, and the University of Michigan Transportation Research Institute, to conduct the Automotive Collision Avoidance System Field Operational Test (ACAS FOT) program that developed a state-of-the-art rear-end crash avoidance system with forward crash warning and adaptive cruise control, including a 1-year field operational test employing laypersons driving ACAS-equipped vehicles. An independent evaluation was conducted by the Volpe Center to assess safety benefits, driver acceptance and system performance.

This paper presents background and results from the recent CAMP Forward Crash Warning work and ACAS FOT.

OVERVIEW OF CAMP FCW FINDINGS

The more recent Crash Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) efforts build upon the foundation provided by the human factors work conducted in the previous CAMP FCW system program [9]. This previous work focused on developing FCW timing and interface requirements for closing alerts; that is, alerts intended to warn the driver when they are approaching a vehicle ahead too rapidly (these alerts can be contrasted with tailgating advisories). The follow-on efforts reported here continue this effort, and involved two major lines of research. The interested reader is referred to [7] and [6] for a more detailed discussion of this research.

One line of research is aimed at understanding the relationship between drivers' last-second braking and steering maneuver behavior under closed-course versus National Advanced Driving Simulator (NADS) conditions. The documentation of this effort is in the final stages, and will not be discussed further here. A second line of research, which is the focus of this paper, is primarily aimed at evaluating and potentially refining the preliminary crash alert timing approach developed in the previous CAMP FCW project under a wider range of conditions. Key to driver acceptance of FCW technology is appropriate crash alert timing, which refers to the necessary underlying vehicle-to-vehicle kinematic (or approach) conditions for triggering the onset of crash alerts. The goal of the alert timing approach is to allow the driver enough time to avoid the crash, and yet avoid annoying the driver with alerts perceived as occurring too early or unnecessary.

As in the previous CAMP FCW research, this research was conducted with a surrogate target, test track (or closed-course) methodology, which allows driver behavior to be safely observed under controlled, real approach, rear-end crash scenario conditions. As illustrated in Figure 1, this methodology involves three vehicles— a mock lead vehicle (or surrogate target), a lead vehicle (which tows this mock vehicle), and a subject vehicle that is driven by the test participant. The surrogate target was designed to allow for safe impacts at low impact velocities (up to 10 miles per hour velocity differential) without sustaining permanent damage. The surrogate target consists of a molded composite mock-up of the rear half of a passenger car mounted on an impact-absorbing trailer that is towed via a collapsible beam. The braking level of the lead vehicle, as well as that of the yoked surrogate target, is controlled via an on-board computer operated by the back-seat experimenter in the subject vehicle.

This test track methodology provides a very realistic physical and perceptual representation of what a driver experiences during in-lane approaches to a vehicle. This realistic representation is felt to be of critical importance for ensuring drivers' perception of crash threat under these experimental conditions are, to the extent possible, representative of those obtained during in-traffic, real world driving conditions. Moreover, this approach is intended to increase the likelihood that the experimental results observed will generalize to real world driving conditions.

In order to ensure the safety of the test participant and afford the participant every possible opportunity to perform unassisted last-second maneuvers, a trained test driver accompanies the participant. The test driver rides in the front passenger seat with access to both an override brake pedal and add-on steering wheel to prevent collisions with the surrogate target. In addition, the test driver has access to a "bail out" crash alert via headphones (which signifies to the test driver to take control of the vehicle), and a curtain divider is used to prevent the test participant from observing the foot behavior of the test driver (e.g., the foot hovering above override brake pedal).

The need for obtaining data under these test conditions is dictated by the infrequency of near and actual collisions in the real world (as was evident in the ACAS FOT data), the sparseness of electronic

Figure 1. Surrogate target (lead vehicle) methodology employed at the General Motors Proving Ground (site of the majority of CAMP FCW research).

crash recording data available during these situations, and the inherent safety and logistic issues surrounding gathering driver's last-second maneuver data under in-traffic conditions. Furthermore, attempts to define crash alert timing based on research that places drivers under minimal risk or no crash risk (e.g., driving simulator) conditions has the potential to lead to alerts that occur too late [9, 10].

In developing a FCW timing approach, two fundamental driver behavior parameters should be considered. These parameters serve as input into vehicle-to-vehicle kinematic equations that determine, given a set of assumptions, the alert range necessary to assist the driver to avoid a potential crash. The first driver behavior parameter is the time duration required for the driver to respond to the crash alert and begin braking, referred to as driver brake reaction time (or brake RT). The second driver behavior parameter needed for a crash alert timing approach is the driver deceleration (or braking) behavior in response to the FCW alert under a wide range of vehicle-to-vehicle kinematic conditions.

Both of these fundamental driver behavior parameters were explored in the previous CAMP FCW work by having drivers perform last-second braking judgments under alerted conditions and exposing drivers to an unexpected (surprise) rear-end crash scenario. The CAMP FCW follow-on research reported here is aimed at continuing to develop assumptions for these parameters under a wider range of conditions. This research employed four different types of methodological approaches/research strategies, each of which will now be described with the corresponding key results observed using these strategies. It should be stressed that these research strategies can be adapted in a relatively straightforward fashion to address interface and timing. Indeed, these strategies have already been embraced and adapted in recent research aimed at backing warning systems [12].

Last-Second Braking and Steering Maneuvers

In the earlier CAMP FCW work [9], drivers performed last-second braking maneuvers under various in-lane approaches using two different braking instructions. The first instruction asked drivers to maintain their speed and brake at the last second possible in order to avoid colliding with the surrogate target using "normal" braking intensity or pressure. (Note that this braking instruction is intended to explore the aggressive end of the "normal" braking envelope rather than more nominal, normal braking behavior.) The second instruction asked drivers to maintain their speed and brake at the last second possible to avoid colliding with the target using "hard" braking intensity or pressure. These data were used to identify drivers' perceptions of normal and non-normal braking envelopes, and to generate a brake onset model which estimates the assumed driver deceleration in response to a FCW alert based on prevailing vehicle-to-vehicle kinematic conditions. An underlying assumption of this approach is that alert timing based on rules for judging threatening conditions that are different from those employed by drivers may well be considered unnatural and unacceptable by drivers.

Unlike the earlier CAMP FCW work, the current study examined both last-second braking and last-second steering maneuvers, both normal and long (3-second) following headway conditions, and in-lane approaches to a lead vehicle moving at a slower but constant speed (The previous CAMP work only examined lead vehicle stationary and lead vehicle braking scenarios). This additional last-second steering data was used to examine the extent to which a FCW timing approach based on driver braking

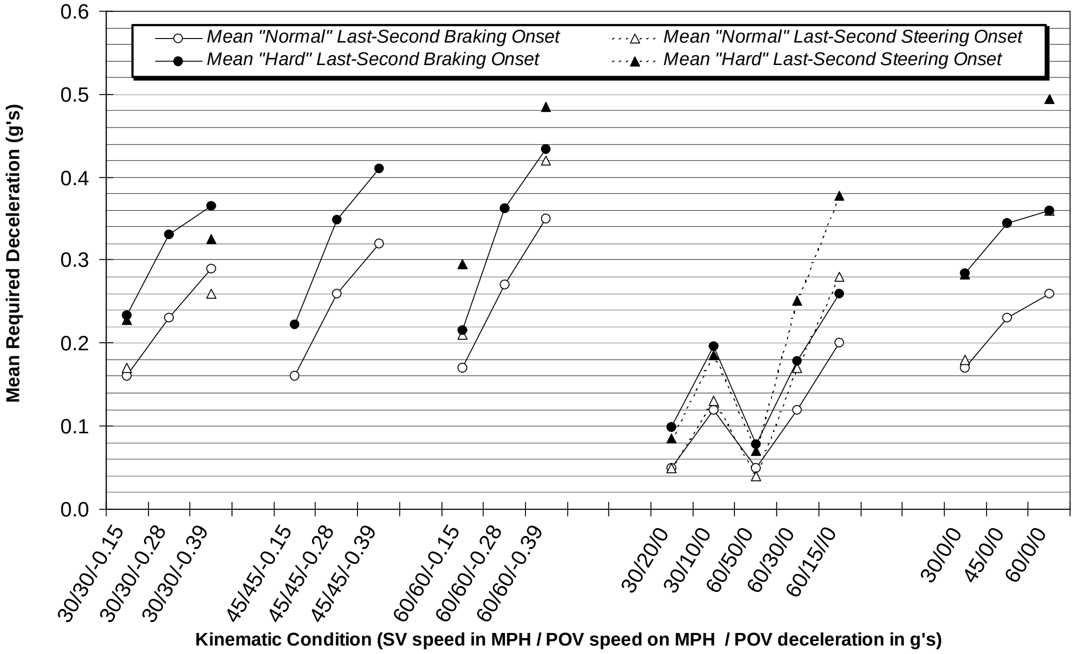

Figure 2. Mean “normal” and “hard” required deceleration values at last-second braking onset and last-second steering onset for each SV speed, POV speed, and POV deceleration profile combination. SV refers to the following, Subject Vehicle, and POV refers to the Principle Other Vehicle (in this case, the lead vehicle).

assumptions could annoy drivers intending to perform a lane-change maneuver around the vehicle ahead. Drivers performed last-second steering maneuvers using two different steering instructions, which parallel the last-second braking (intensity) instructions described above. The first instruction asked drivers to maintain their speed and change lanes at the last second they “normally would to go around the target”. The second instruction asked drivers to maintain their speed and change lanes at the last second they “possibly could to avoid colliding with the target”. The last-second braking and steering onsets were then characterized in terms of the (constant) required deceleration level to avoid a collision at last-second maneuver onset and the time-to-collision at last-second maneuver onset (i.e., the time before impact if prevailing conditions continue).

There are a number of commonalities between the current and the previous CAMP FCW last-second braking study [9] that enabled the possibility of combining these data sets based on comparable results observed across studies. First, a subset of the Kiefer et al. last-second braking scenarios was included in the current study. Second, identical age and gender requirements were used in both studies. Third, both studies were conducted on a straight, level, smooth, asphalt, dry road under daytime conditions. The previous Kiefer et al. data was gathered at the General Motors Milford Proving Ground test site in Milford, Michigan (shown in Figure 1), and the more recent data was gathered at the Transportation Research Center in East Liberty, Ohio.

Results indicated that the differences observed in last-second braking onset behavior as a function of test site (Milford Proving Ground versus Transportation Research Center), age (20-30, 40-50, and 60-70 year olds), and gender (male, female) were relatively small in magnitude. Hence, the previous and current last-second maneuver datasets were combined for further analyses and modeling. Second, as shown in Figure 2, braking (as well as steering) onsets varied as a function of maneuver speed and lead vehicle deceleration conditions, and the relative timing of last-second braking versus last-second steering onsets was highly dependent on the kinematic conditions. These results provide evidence against a FCW timing approach that assumes a fixed driver deceleration (or fixed time-to-collision) value, and suggests that under some conditions, a FCW timing approach that only assumes a braking response by the driver could result in presenting alerts to drivers performing intentional lane change maneuvers.

However, estimating the potential magnitude/importance of alerts being issued prior to intended lane-change maneuver under real-world conditions is difficult. First, it should be kept in mind that drivers will not always have the opportunity to appropriately execute a steering maneuver. Second, it remains unclear the extent to which drivers would find alerts that occur prior to intentional last-second, normal lane changes annoying. More generally, the annoyance level potentially associated with these alerts, as well as other alerts perceived as too early or unnecessary, will ultimately be weighted against the driver's perception of alert appropriateness and system benefits under a rich set of varied real-world experiences with the FCW system. Consequently, extensive field operational testing was necessary (described shortly), at a minimum, to better understand what types and levels of false alarms are acceptable to drivers.

The last-second braking data from this combined dataset (which includes 3,536 last-second braking judgment trials and 790 last-second steering judgment trials) were then modeled for the purpose of predicting hard braking onset (or driver deceleration behavior in response to the alert). Recall that driver deceleration behavior in response to the alert is one of two driver behavior parameters needed for a crash alert timing approach (the other parameter being driver brake reaction time to the FCW alert).

A wide range of potential time-based and deceleration-based predictors was explored. Inverse time-to-collision (TTC) was found to be the single most important predictor of whether or not a braking onset scenario was a normal or hard, last-second braking onset scenario. The key component of this model is the inverse TTC term, defined as the difference in speed between the lead and following vehicles divided by the range between these two vehicles (or Δ Velocity / Range). It should be noted that although TTC and inverse TTC are mathematically interchangeable, the inverse TTC measure provides a more parsimonious approach for characterizing drivers' perception of normal versus hard braking envelopes [10].

The inverse TTC model was developed using a logistic regression approach that predicts the probability a driver is in a hard braking scenario (and hence, not in a normal braking scenario). This model can be elegantly described as a model that assumes that the driver deceleration response in response to the crash alert is based on an inverse TTC threshold that decreases linearly with driver speed. An examination of the model fit across the approach conditions tested, as well as a domain of validity check across a much wider range of approach conditions, provided support for the robustness of this approach.

It is important to note that TTC can also be perceptually defined as the angular size of the approaching object divided by its angular speed [11,17], and hence, inverse TTC is directly tied to the visual looming properties or angular expansion of the lead vehicle. Furthermore, inverse TTC has been found to be a robust measure for describing drivers' ability to perceive relative motion under near threshold relative speed conditions [3]. Note that just as the visual angle subtended by the lead vehicle becomes "optically explosive" immediately prior to a collision [4, 16], changes in the inverse TTC measure (unlike the TTC measure) become more prominent as TTC diminishes to low TTC values.

The inverse TTC model has several potential advantages over the previous CAMP FCW required deceleration model of last-second braking [9], although it should be noted that both models provide comparable predictions. First, the current model offers greater flexibility by operating in the "probability of hard braking" domain, which allows the designer to modulate the "probability of hard braking onset" assumption based on inputs that may be available to the FCW system (e.g., driver age, driver eye movement location, driver attentional state, road/weather conditions, suspected lane change conditions). Second, the current brake onset model does not require accurate knowledge of lead vehicle deceleration, and instead merely requires knowledge of whether or not the lead vehicle is stationary, moving and braking, or moving and not braking. This is of some practical importance since obtaining real-time, accurate knowledge of lead vehicle deceleration behavior is technically challenging.

The performance of the inverse TTC model suggests that drivers do not use detailed knowledge of lead vehicle deceleration when making hard braking decisions. However, accurate knowledge of lead vehicle deceleration is still desirable for FCW timing purposes, since this knowledge can be used to improve predictions associated with calculating the assumed Delay Time Range, which, along with the assumed Braking Onset Range, is used to calculate FCW Warning Range [9]. The Delay Time Range is calculated based on the projected change in range to the vehicle ahead, given prevailing speed and deceleration levels of the lead and following vehicles, during an interval which is composed of the summation of various system delay times. These system delay times include driver brake RT, the time between when the alert criterion is violated and the onset of the crash alert, and the time between brake onset and actual vehicle slowing as a result of braking. The Braking Onset Range corresponds to the assumed range at which the vehicle begins to actually slow as a result of braking.

In conclusion, these results suggest that the inverse TTC model of braking onset provides a promising component for a FCW timing approach. Furthermore, inverse TTC appears to be a key element of the underlying mental process drivers use in deciding when they are in their normal versus hard braking envelope.

Surprise Lead Vehicle Braking Trials

The surprise (unexpected) lead vehicle braking technique has been used rather extensively in previous and recent CAMP FCW efforts to address the extent to which a wide range of factors impact the effectiveness of the CAMP FCW timing approach developed in the initial CAMP FCW project [9]. This more recent surprise trial work [6] examined the extent to which alert effectiveness is impacted by driver characteristics, environmental factors, interface design, distraction task/activity, kinematic conditions, and training/false alarms. Seventeen distinct surprise trials conditions were examined involving a total of 260 drivers. The alert timing approach employed was based on the required deceleration approach described in [7], coupled with a 1.52 second brake RT (or 95th percentile brake RT) assumption [9]. In addition, this work examined the degree to which knowledge of the factors examined would be useful for modifying the alert timing approach, as well as the benefits of a FCW alert (or alert presence). To investigate these issues, a surprise trial technique (illustrated in Figure 3) was employed in which the driver is distracted intentionally by the on-board experimenter immediately prior to the unexpected lead vehicle braking (or closing) event, which inevitably leads to a FCW alert presentation. Distraction techniques included both eyes-forward tasks (e.g., interacting with a voice recognition system to obtain navigation directions) and tasks involving head-down activity (e.g., dialing an unfamiliar set of numbers on a cellular phone mounted on the center console). In addition, much of the current and previous CAMP FCW surprise trials efforts have focused on evaluating a single-stage, dual-modality (auditory plus high head-down visual) FCW alert, in part because this interface is considered favorable from an industry-wide, production-friendly perspective.

Overall, results strongly support the effectiveness of the CAMP FCW alert timing/interface approach evaluated. First, based on test driver intervention rates, this approach was found to be robust, effective, and rated by drivers as appropriate across the wide range of conditions evaluated. Overall, intervention rates in the FCW alert and no-FCW alert conditions were 6.8% and 13.2%, respectively, which provides support for the overall utility of FCW alerts. The former intervention rate may be reduced if drivers received “valid” FCW alert experience/training, which was not provided here.

Second, these test driver interventions were restricted to tasks involving head-down glance activity, and never occurred for the eyes-forward distraction tasks examined. Furthermore, interventions occurred when the driver was looking down at the phone at FCW alert onset. Hence, a promising means of improving the CAMP FCW alert timing approach appears to involve sensing driver eye movement location, and more precisely, sensing when the driver is looking down (or away from the forward scene) instead of looking forward at the scene ahead. This sensing capability would not only improve alert timeliness for valid alerts issued when the driver is looking down, but just as importantly, such a capability would reduce the number of alerts perceived as occurring too early or unnecessary by the driver because they were already looking at the forward scene and purportedly aware of the vehicle ahead. Such a capability is highly desirable based on the ACAS FOT results that will be discussed below.

Third, 85th percentile driver brake RT values to the FCW alert under these surprise trial conditions have remained remarkably stable across the seven driver distraction tasks which have been examined (which includes previous CAMP FCW surprise trial work), ranging between 1.03 and 1.22 seconds. As might be expected, the 95th percentile brake RT values across these tasks tend to vary more widely, ranging from 1.10 to 1.73 seconds. These upper percentile values correspond well to other relevant sources of surprise driver brake RT data [5, 14, 15], and hence, are viable candidates for driver brake RT assumptions employed in FCW timing approaches, which is one of two driver behavior parameters desired for a crash alert timing approach.

Fourth, although both negative and positive effects of “cry wolf” false alarms were observed under these experimental conditions, it is somewhat tenuous to generalize these results to the rich and

Figure 3. Surprise trial method (Unexpected lead vehicle braking).

varied nature of drivers' experiences under day-to-day, naturalistic driving conditions with both valid FCW alerts and alerts perceived as too early or unnecessary by the driver. Indeed, gaining a deeper understanding of drivers' tolerances of false alarms provides an important underlying rationale for conducting the ACAS FOT project described below.

Time-to-Collision Judgments

The last-second braking data reported above suggests that the inverse TTC measure provides a parsimonious approach for characterizing driver's perception of normal versus hard braking envelopes. Hence, drivers' perception of the instant they feel that they would have collided with the vehicle ahead, and the relationship between perceived and actual TTC are of inherent interest. The perceived TTC measure was obtained here by occluding the driver's vision using liquid-crystal glasses (as shown in Figure 4) during the last phase of an in-lane approach to a lead vehicle. (See [13] for a more detailed description of these occlusion glasses.) After vision was occluded (at which point the test driver took control of the vehicle), the driver was to press a button the instant they felt that they would have collided with the vehicle ahead (assuming prevailing vehicle-to-vehicle kinematic conditions and existing collision course trajectories continue).

Nearly all previous TTC judgment studies intended for automotive application have been gathered with scenes presented under laboratory or driving simulator conditions [4, 18]. These scenes have distinctly different visual properties than real-world scenes that may impact TTC judgments (e.g., reduced peripheral vision, degraded binocular distance cues, and artificial scene texture gradients), and hence, drivers' perception of crash threat. (Indeed, this issue underlies the motivation for the current CAMP FCW NADS research briefly mentioned earlier in the paper.)

This study provides the most extensive set (known to the authors) of TTC judgment data ever gathered under realistic driving conditions. The current study examined TTC estimation under 12 combinations of driver speed and relative velocity, with driver speeds ranging between 30 and 60 MPH (48 and 97 km/h) and relative speeds ranging between 10 and 30 MPH (16 and 48 km/h). Results indicated that TTC was consistently underestimated. The TTC ratio (perceived TTC/actual TTC) increased as driver speed decreased and as relative speed increased. These ratios were largely unaffected by age, gender, actual TTC (3.6 or 5.6 seconds), viewing time (1-second versus continuous), and the presence of an eyes-forward, mental addition distraction task. It is of importance to note that the experimental manipulations of limiting viewing time (to 1 seconds) and/or introducing a concurrent (mental addition) distraction task were explicitly intended to represent distracted driver conditions. The elevated importance of TTC estimation coupled with the extreme salience of the lead vehicle looming behavior under the low TTC conditions examined appears to mitigate any effects of the independent variables examined on TTC estimation. In an analysis aimed at examining extreme TTC judgments, which may play an

Figure 4. Time-to-collision judgment technique using occlusion glasses (1-second glimpse condition shown).

underlying role in rear-end accident causation, increases in age and relative velocity were found to lead to higher probabilities of TTC overestimation (i.e., when perceived TTC exceeds actual TTC). With an eye toward developing an alert timing approach, these results suggest that under these low TTC conditions drivers estimate TTC in a relatively uniform fashion and that they are capable of providing this estimate based on a brief glimpse to the vehicle ahead after a period of losing visual and/or cognitive contact to the lead vehicle. Such a glimpse may occur following a FCW alert issued to a driver looking down, which is intended to trigger the driver to look toward the forward scene.

From a more theoretical perspective, these results tend to support for the view that drivers employ a direct, efficient, and automatic optic flow heuristic for making TTC estimations (at least under these low TTC conditions), which may be modified based on speed and relative velocity conditions [8]. Under this heuristic, drivers estimate TTC by operating directly on the visual scene and associated looming properties of the lead vehicle.

"First Look" Maneuvers

The "first look" technique, like the TTC estimation technique described above, is a visual occlusion technique being employed to further understand drivers' decision-making and avoidance maneuver behavior in rear-end crash scenarios. (It should be briefly noted that the data generated from these CAMP FCW occlusion techniques may provide a useful tool for validating/calibrating similar data gathered under simulator and laboratory approach conditions.) This technique is aimed at quantifying a surprised driver's reaction to a collision alert, and assessing the adequacy of a FCW timing approach under a wider range of approach conditions than can be practically attained using the "1 trial per subject" surprise trial technique described above.

After receiving a FCW alert, the surprised driver must quickly decide upon and execute a crash avoidance maneuver. In order to create what is considered an extreme form of driver distraction (i.e., a surprised driver) in which the driver has lost all visual and/or cognitive contact with the vehicle ahead, this first look technique (illustrated in Figure 5) involves blocking a portion of the driver's central vision with a CAMP-designed (liquid-crystal) occlusion window during the entire initial phase of an in-lane approach such that the driver could not see the lead vehicle. (Note that drivers still received visual information available through the side windows and portions of the front windshield, which is important since non-central visual information plays an important role in speed perception.) During the last phase of this in-lane approach, the driver's vision is suddenly "opened" at a point in time intended (based on the surprise trial dataset described above) to correspond to when a driver caught looking down would get their "first look" at the vehicle ahead after receiving a FCW alert. A driver is presumed to be in an alerted state shortly after a FCW alert is issued, which in this case corresponds to the timing of the window opening. Upon vision opening, the driver's task was to avoid colliding with the lead vehicle.

Drivers were encouraged to brake if at all possible unless they were not closing on the vehicle ahead (referred to as catch trials), in which case they are instructed to refrain from either braking or steering. If the driver is closing in on the vehicle ahead after vision opening, two steps are taken to prevent the driver from adopting a strategy of either always braking or always steering. To discourage the driver from an "always braking" strategy, trials are included with very late window opening timing, where a last-second steering avoidance response is predicted to be favored over braking (based on the CAMP FCW last-second steering data reported in [7]). To discourage the driver from adopting an "always steering" strategy, a trailing vehicle is present which passes in and out of the

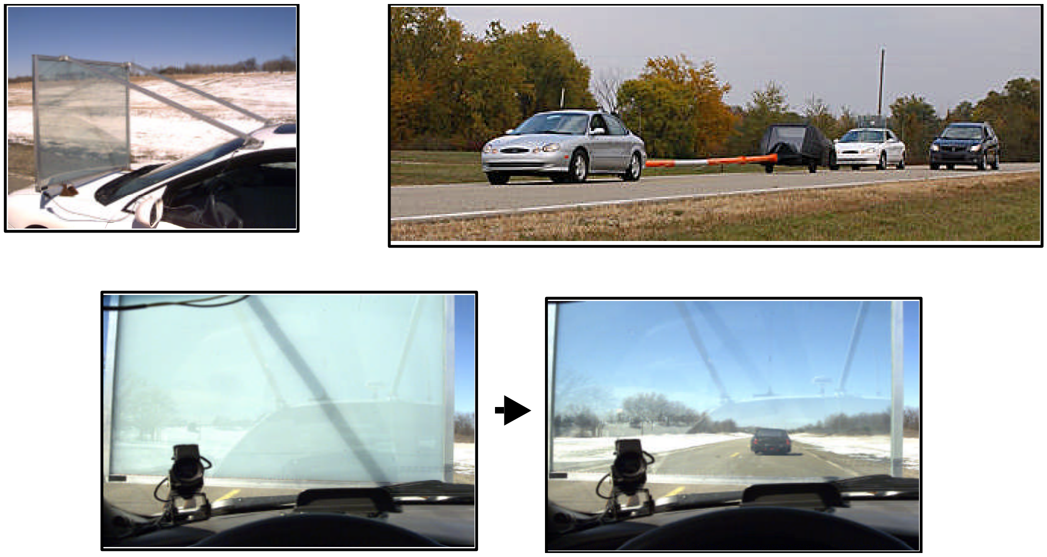

Figure 5. "First look" (extreme distraction) technique using the window occlusion method.

driver's blind spot in the adjacent lane and effectively discourages the driver from reflexively making a steering response.

Results from this study indicated that drivers were able to execute an unassisted, successful braking maneuver for over 85% of the trials. These results were obtained across a much wider range of vehicle-to-vehicle (kinematic) approach conditions than have been examined under surprise trial conditions. Hence, these results suggest that drivers can execute an appropriate crash avoidance maneuver under the alert timing assumptions evaluated, and under conditions that may have increased decision-making complexity relative to what drivers experienced in the previously reported surprise trial (unexpected lead vehicle braking) studies. These results, along with the TTC estimation results reported above, suggest that the driver can quickly assess TTC and make the appropriate crash avoidance maneuver under CAMP FCW alert timing assumptions.

Furthermore, a comparison of driver behavior under these "first look" conditions relative to the surprise trial conditions discussed above indicates the first look method appears to be a valid, efficient, and promising method for exploring the consequences of FCW alert timing. These comparison results indicate that required decelerations at brake onset and peak decelerations throughout the braking maneuver were somewhat higher under the current conditions relative to the matched surprise trial data set. These results suggest that this first look method represents a rather extreme form of driver distraction, and hence, this method may provide a conservative estimate of FCW alert effectiveness from a crash avoidance perspective. In addition, it is felt that this method provides a promising technique for generating decision-making and maneuver behavior representative of that which would be obtained from drivers under real world, rear-end crash scenarios.

This method could be used to explore the consequences of later FCW alert timing, which may serve to reduce false alarms, and hence, potentially increase the overall "credibility", acceptability, and safety effectiveness of the FCW alert system. Indeed, as will be discussed in the next section, reducing the number of false alarms drivers experience to a level that is considered acceptable by drivers while still maintaining effective valid alert timing remains a formidable challenge for FCW deployment and effectiveness.

More generally, it should be noted that there is a general lack of both age and gender effects under the actual FCW alert (i.e., surprise trial) and simulated FCW alert (i.e., visual occlusion) conditions examined in previous and current CAMP FCW efforts. This suggests that the FCW alert information may be an effective means of equalizing (or neutralizing) drivers in their ability to avoid rear-end crashes, and that a "one-size-fits all" FCW alert timing approach for closing alerts may be feasible.

OVERVIEW OF ACAS FOT FINDINGS

The goal of the Automotive Collision Avoidance System Field Operational Test (or ACAS FOT) project was to further the science and understanding of Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC) systems by conducting an extensive FOT with lay drivers. The FOT was designed to address numerous issues dealing with the use and deployment of FCW and ACC systems. These issues revolved around examining the potential implications of these systems from both a traffic safety and driver acceptance perspective. The following is a summary derived from [1] and [2].

As the team leader for this project, General Motors was responsible for program management, overall integration of the various subcomponents and their associated software, threat assessment functions, and activities associated with predictions of vehicle location and road geometry. Delco Electronics & Safety was responsible for the Forward Looking Radar system, the ACC system, the Vision and Scene tracking systems, the Target Selection system and the Driver Vehicle Interface system that included a head-up display (HUD) which was used to display ACC- and FCW-related information. Hughes Research Laboratories was responsible for the Data Fusion system designed for the purpose of accurately determining forward road geometry. Delphi Chassis was responsible for developing the Intelligent Brake Control subsystem for the ACC system. Finally, the University of Michigan Transportation Research Institute (UMTRI) was responsible for the design and implementation of the Data Acquisition system, as well as the design and conduct of the formal FOT. Both UMTRI and General Motors were responsible for conducting the analysis of the FOT data.

The ACAS FOT program began in June of 1999 and was completed in November of 2004. It was organized into two phases. Phase I ran from June 1999 to December 2001. In this phase, the various ACAS subsystems were selected and developed using five Engineering Development vehicles. Once satisfactory performance was achieved, these subsystems were then integrated into a single Prototype Vehicle.

Phase II of the ACAS FOT program began in January of 2002 and was completed in November of 2004. In this phase, lessons learned from the Prototype Vehicle were used to install the ACAS system into two Pilot Phase Vehicles with FOT-deployment-level packaging. Further improvements were then made to the system and these two vehicles along with the 11 Deployment Vehicles were then built-up for a total of 13 Deployment Vehicles available for the FOT.

The FCW and ACC systems were developed, integrated and ultimately packaged in the 13 Buick LeSabre (2002 model year) Deployment Vehicles. Both FCW tailgating advisories and closing alerts were provided to the driver on a HUD via a graded looming approach shown in Figure 6. A small blue-green “vehicle ahead” display is provided when the system determines a vehicle is in the path of the driver’s vehicle. For tailgating advisories and closing alerts, as the potential for a rear-end conflict increases, the icon turns to an amber color (referred to as a cautionary alert) and grows in size with the icon size dependent on the degree of predicted conflict. A final flashing alert (referred to as an imminent alert) consists of both a red/yellow flashing visual display and a series of warning beeps. Whereas the timing of the cautionary alerts was adjustable by the driver, imminent alert timing was not adjustable.

The ACC system evaluated is an enhancement to traditional cruise control. This feature allows the driver to keep cruise control engaged in moderate traffic conditions without having to constantly reset their cruise control. The system could apply limited braking or acceleration of the vehicle automatically to maintain a driver-selected follow distance to the vehicle ahead (which ranged from 1-2 second time headway). ACC braking was limited to about 0.3 g's (2.94 m/sec^2) of deceleration, which is comparable to moderate application of the vehicle's brakes.

These Deployment Vehicles were then given to 96 test subjects who, after receiving training on the ACAS system, drove these vehicles as their own personal cars for three or four weeks. The 96 lay drivers chosen for this experiment were randomly selected from three age groups (20-30, 40-50, and 60-70 years old) balanced for gender. During the first week of each subject’s use, the ACAS features were not available to the drivers. During the subsequent weeks, the ACAS features were available. A robust data acquisition system was employed to capture a wealth of data from each driver’s use of the ACAS cars. This data included a myriad of signals from the host car’s J1939 data bus as well as visual images of the road ahead, and the driver’s face. Radar tracks of cars, stationary objects, and other “targets” ahead were detected by the radar. Altogether some 1.4 terabytes of information were collected for analyses.

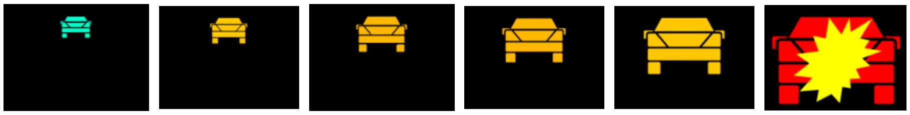

Figure 6. ACAS FOT graded, looming visual alert approach.

Table 1.
Overview of ACAS FOT safety and acceptance findings for Forward Collision Warning and Adaptive Cruise Control.

	Safety	*Acceptance*
Forward Collision Warning	- Reduced tailgating behavior - "Valuable" alerts identified - No broad "closing conflict" effect - No unintended safety consequences	- Purchase interest low - Too many alerts perceived as unnecessary
Adaptive Cruise Control	- Reduced tailgating behavior - Increased lane dwelling - Perceived as having more safety value than FCW - No unintended safety consequences	- Purchase interest high (without price target)

Interviews, questionnaires, and focus groups were also employed to capture the test participants' subjective evaluations.

When the FOT began in March 2003, the initial acceptance response of the ACAS system was much less positive than was reported by participants during earlier pilot testing. This dissatisfaction was based on what drivers considered to be false alarms (i.e., alerts perceived as too early or unnecessary). About half of the alerts were due to stationary objects along the roadside being detected by the radar and erroneously classified as "threats". Many other alerts occurred under conditions that drivers simply felt did not warrant an alert.

To address this situation, a 3-phased approach was implemented. First, in order to ensure sufficient information was garnered from the original algorithm (called Algorithm A), a total of 15 drivers drove with this original set of software. While this testing was underway, an improved algorithm was quickly developed and installed on the ACAS vehicles for a second set of 15 drivers (called Algorithm B). This software included several improvements over Algorithm A and also eliminated all alerts from stationary objects that the radar had never before seen moving during the approach (e.g., a roadside sign). Algorithm B still issued alerts to stationary objects that the radar had previously seen moving during an approach, such as when a lead vehicle came to a stop. Finally, a very ambitious set of software was developed (called Algorithm C) which restored alerts from "never before seen moving" stationary objects and added a host of features to further reduce the number of false alarms. The remaining 66 test subjects drove their vehicles with Algorithm C as the operating software. Overall, the efforts made to reduce false alarms produced approximately an order of magnitude reduction in these alarms from the first algorithm implemented in the Prototype vehicle to the most advanced algorithm that was ultimately employed in the formal ACAS FOT.

It is important to emphasize that the FCW and ACC sub-systems examined could potentially reduce the incidence of rear-end crashes, as well as the harm caused by such crashes, in primarily two different ways. First, these systems could reduce the amount of tailgating behavior, that is, the amount of time drivers spend following a vehicle ahead at short time headways under "steady state" driving conditions. A lengthening of headway times under these conditions can provide the driver with additional time to respond should an unexpected rear-end crash scenario unfold. Secondly, the FCW system may at times (e.g., when the driver is distracted) alert the driver to an approach (or closing) conflict earlier than the driver would have detected such a conflict. These approach conflicts, as well as tailgating behavior, can ultimately lead to a rear-end crash.

A high-level overview of the ACC and FCW safety- and acceptance-related results are shown in Table 1. Results indicated that both the FCW and ACC sub-systems reduced the incidence of tailgating behavior relative to manual driving without the support of these systems. Overall, as can be seen in Figure 7, the incidence of less than 1-second time headways were 26% with FCW system support, and

30% without FCW system support. This overall FCW headway lengthening effect was also observed at 0.1 second headway steps starting from cumulative time headway at less than 1.6 second headways all the way down to cumulative time headway at less than 0.5 second headways. A more detailed examination indicated that this effect was restricted to daytime driving and freeway driving conditions.

Perhaps more notably, as can be seen in Figure 8 (which shows headways under heavy traffic conditions), the incidence of less than 1-second time headways was three times lower during ACC relative to manual driving. This may in part explain why drivers' ratings of whether the system increased their driving safety were more positive for ACC than corresponding ratings for FCW. It should be pointed out that although this lengthening of headway times caused by ACC will naturally lead to increased cut-in behavior by other drivers, the warm driver acceptance of ACC suggests that the perceived ACC benefits clearly outweigh this potential annoyance.

The more dramatic effects of ACC on tailgating behavior are in all likelihood a direct result of the system preventing the driver from selecting an ACC gap (or time headway) setting of less than 1-second following time. The exact source of the FCW headway lengthening effect on tailgating is less clear, but can be potentially attributed to either the FCW tailgating advisory display (or possibly a transfer of training from the ACC system) increasing the driver's general awareness of their car following behavior.

On the other hand, evidence that the FCW and ACC systems reduced approach conflict behavior was mixed. Approach conflict metrics examined included the frequency of imminent alerts (where "silent" or "virtual" alerts were examined when the ACAS system was not activated), required deceleration to avoid impact and time-to-collision at brake onset, as well as peak conflict measures during approach events to a lead vehicle. Results indicated that the FCW system did not have a broad effect on reducing approach conflict behavior. Nevertheless, a small number of FCW imminent alert incidents were identified that were judged to have increased drivers' awareness of a potential rear-end crash and/or encouraged the driver to brake. Hence, the potential for the FCW system to help the driver avoid rear-end crashes and reduce the harm caused by such crashes was demonstrated.

With respect to ACC, it can be hypothesized that this system has at least the potential to increase approach conflict behavior, either because of the manner in which ACC controls the vehicle in approach situations and/or due to the choices drivers make in allowing ACC control in their assumed supervisory role. Results indicated that ACC did not negatively impact approach conflict behavior. On the contrary, it appears that ACC may reduce risks associated with lane changes by decreasing passing behavior (thereby increasing lane dwelling) and increasing the range at which drivers initiate certain lane-change-and-passing maneuvers on freeways (presumably to avoid ACC braking during passing).

Results did not indicate any unintended safety consequences of these systems (e.g., no notable increases were observed in secondary task behavior such as cell phone conversation, passenger conversation, eating, grooming, smoking). However, it should be noted that the increased percent driving time with ACC relative to conventional cruise control (overall, 37% versus 20% usage) was evident across all driving conditions, with the most notable increase of ACC usage occurring under heavy traffic conditions.

In addition, the rare occurrence of events in which the ACC system provided the maximum level of ACC braking was observed almost exclusively under surface street conditions. The rate of these rare events dropped substantially over the course of the three weeks of driving with ACAS enabled. Overall, there is a clear suggestion that drivers strongly preferred intervening with manual braking before the ACC applied its maximum braking authority, suggesting that drivers were not being overly reliant on ACC braking. Finally, a search for drivers who may have been experimenting with ACC and FCW systems failed to yield a single ACC maximum braking incident caused by driver experimentation, and suggested that the heightened level of driver attentiveness during this experimentation may serve to mitigate the risks associated with this activity. Driver acceptance of the FCW system was clearly mixed, and uniformly high for the ACC system. Overall, the older drivers tended to be more accepting of these systems. Without a hypothetical system cost, 45% and 75% of drivers indicated positive purchase interest toward the FCW and ACC systems, respectively. With a $1000 system cost for each system individually or a $1,600 combined (ACC plus FCW) system cost, positive purchase interest dropped to between 30% and 35%. The higher purchase interest in ACC may in large part be due to the fact that ACC profoundly reduces the workload and stress associated with the everyday task of car following (e.g., brake apply rates were 25 times lower under freeway conditions than with manual driving), along with the lack of FCW alert "credibility".

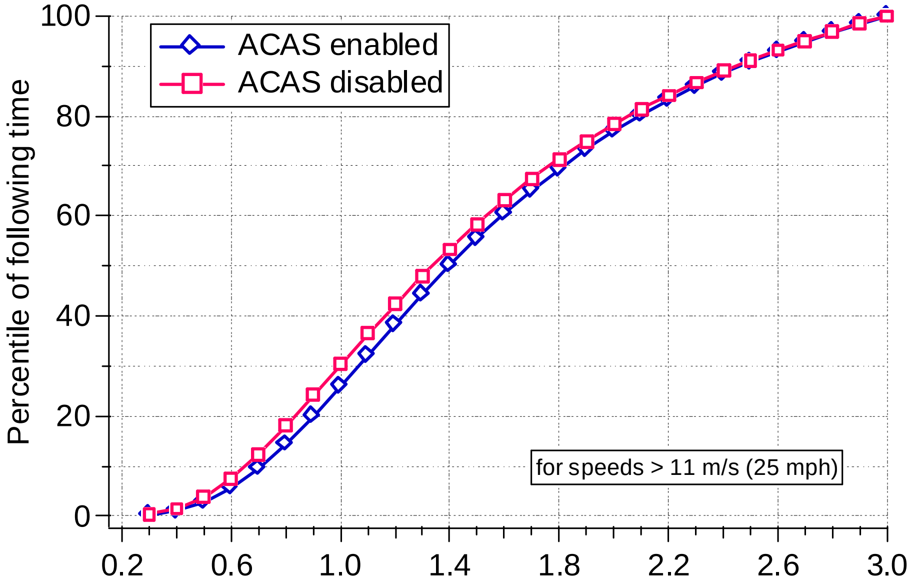

Figure 7. Cumulative distribution of headway times with and without ACAS Forward Collision Warning (FCW) system support.

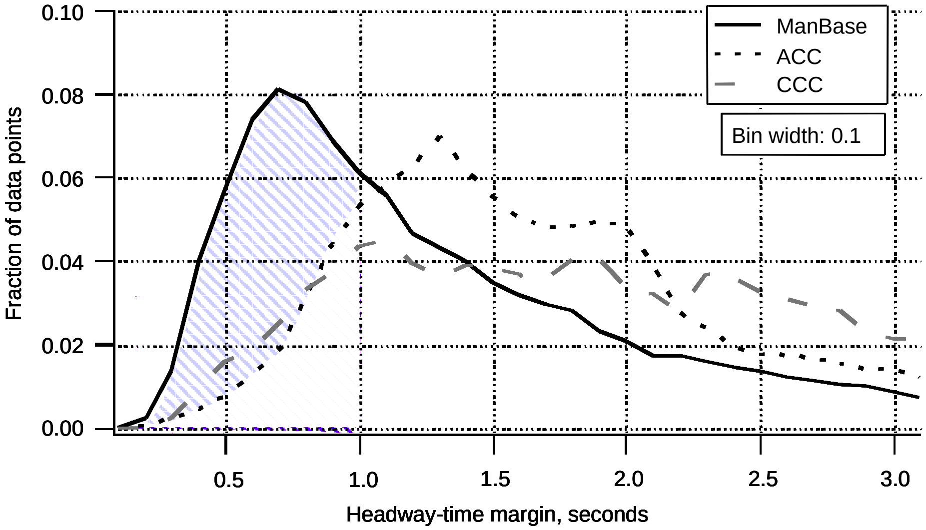

Figure 8. Cumulative distribution of headway times without cruise control, with Adaptive Cruise Control (ACC), and with Conventional Cruise Control (CCC) under heavy traffic conditions.

Although the ACAS test participants may not be fully representative (e.g., from an income level or vehicle ownership perspective) of likely buyers for initial ACC- and FCW-equipped production vehicles, these data clearly illustrate the importance of ensuring FCW and ACC systems can be offered to consumers at affordable costs in order to foster deployment of these features.

With respect to FCW, results clearly suggest that further reductions in false alarms (resulting in a higher proportion of "credible" FCW alerts) are needed to ensure widespread FCW system acceptance. Overall, the vast majority of imminent alerts occurred during non-ACC driving. Under these manual driving conditions, imminent alerts occurred at an average rate of 1.44 per 100 miles for drivers using Algorithm C (with alerts occurring primarily on surface streets). In addition, average imminent alert rates varied from 0.08 to 4.34 per 100 miles across drivers.

Roughly one-third of the imminent alerts were issued in response to each of the following three general alert categories: to vehicles that remained in the same lane as the driver during the approach, to roadside out-of-path stationary objects (such as signs and mailboxes), and to vehicles which transitioned in and out of the lane sometime during the approach (e.g., when the lead vehicle was turning or during driver-initiated lane changes). Consequently, it is not surprising that drivers were not observed to brake reflexively to the imminent alert.

The overall impression is that a formidable technical challenge lies ahead in fielding a widely accepted FCW system. Unfortunately, a comparison of subjective results across algorithms investigated, as well as within the 66 drivers experiencing the final algorithm, failed to provide clear direction as to the extent to which false alarms must be reduced in order to ensure widespread acceptance of the FCW system. Nonetheless, the lessons learned in this project have suggested numerous improvements that have the potential to lead to this broader customer acceptability by reducing false alarms. For example, at least for the current state-of-the-art capability, it appears that the requirement levied on the ACAS system to detect "always stationary" vehicles (i.e., vehicles that have never been seen moving by the FCW system) may be ill-advised, based on the high frequency of false alarms to "always stationary" objects (such as signs and mailboxes) relative to the extremely rare occurrence of credible imminent alerts to "always stationary" vehicles.

From the perspective of executing an FOT, this effort demonstrates the value of conducting multiple preliminary mini-FOTs (prior to the formal FOT) to ensure system performance is commensurate with driver expectations. Furthermore, it should be stressed that drivers' acceptance of systems based on short-term exposures can be very misleading.

CONCLUSIONS

In summary, the CAMP FCW and ACAS FOT program have produced pioneering knowledge which can be used to address the rear-end crash problem, as well as other types of crashes. The CAMP FCW project has provided important information with respect to characterizing and modeling drivers' normal and non-normal last-second braking and steering maneuvers (or envelopes), FCW timing and interface approach recommendations, and innovative test-track methodologies which can be used to examine crash avoidance systems under controlled, realistic conditions.

The ACAS FOT augments this information with an immense set of in-traffic, naturalistic data which has provided much needed information on FCW system alert rates and false alarm issues, the immense variation of driver's alert experiences, driver potential acceptance of an FCW system, and FCW system performance requirements. In addition, the ACAS FOT provides an equally rich set of data to understand how drivers choose to use and behave with an ACC system with moderate levels of braking authority.

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