CHAPTER 3

DEVELOPING A FCW SYSTEM CRASH ALERT TIMING AND MODALITY APPROACH VIA HUMAN FACTORS STUDIES

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3 DEVELOPING A FCW SYSTEM CRASH ALERT TIMING AND MODALITY APPROACH VIA HUMAN FACTORS STUDIES

3.1 Preface

The goal of the human factor portion of the CAMP project was to define driver-interface requirements. More specifically, this effort is focused on defining when to present crash alerts (i.e., crash alert timing) and how to present crash alerts to drivers (i.e., the crash alert modality).

The need for obtaining data to define these requirements was dictated by the absence of data under controlled, realistic conditions involving drivers braking to a realistic crash threat. Based primarily on the four closed-courses, human factors studies described in this chapter, a set of minimum driver interface requirements and recommendations were developed, which are discussed in Chapter 4.

The current chapter is conceptually organized into two parts. The first part of this chapter is encompassed by Study 1, referred to as the “baseline study”. This study was aimed at defining crash alert timing for subsequent studies, and asked drivers to perform “last-second” braking maneuvers without FCW system support. The second part of this Chapter is encompassed by Study 2, Study 3, and Study 4, which are collectively referred to as the “Interface Studies". These studies were aimed at defining how to present FCW system crash alerts to drivers, and provided the opportunity to evaluate and validate the crash alert timing approach developed in the baseline study. In these studies, drivers experienced various FCW system crash alert types under both expected and unexpected (surprise) lead vehicle braking conditions. In 2 of these 3 interface studies, drivers were completely unaware the vehicle was equipped with FCW system crash alerts when the surprise-braking event was introduced.

The reader interested in a collective summary (or overview) of both the baseline study and the interface studies is referred to the Executive Summary at the very beginning of this report.

3.2 Abstract for Study 1 – The Baseline Study

The goal of the human factor portion of the CAMP project was to define driver-interface requirements. More specifically, this effort is focused on defining when to present crash alerts (i.e., crash alert timing) and how to present crash alerts to drivers (i.e., the crash alert modality. The primary goal of this first CAMP human factor study was to define a crash alert timing approach for a FCW system by exploring various driver behavior measures.

In this study, a strategy was employed to initially develop a fundamental understanding of the timing and nature of drivers’ “last-second” braking behavior without a FCW system, before conducting the subsequent FCW system driver interface studies. This strategy was taken so that drivers’ perceptions of “normal” and “hard braking” kinematic situations could be properly identified and modeled for FCW system crash alert timing purposes. The underlying assumption

of this experimental strategy is that properly characterizing (i.e., modeling) the kinematic conditions surrounding the hard braking onsets, without FCW system crash alert support will lead to a proper estimate for the assumed driver deceleration (or braking) behavior in response to a FCW system crash alert across a wide variety of initial vehicle-to-vehicle kinematic conditions.

More specifically, in developing a crash alert timing approach for a FCW system, two fundamental driver behavior parameters have to be considered. These parameters serve as input into straightforward vehicle kinematic equations that determine the alert range necessary to avoid a crash. The first parameter is the time it takes for the driver to respond to the crash alert and begin braking (which includes *driver brake reaction time*), and the second parameter is the driver deceleration (or braking) behavior in response to this alert across a wide variety of initial vehicle-to-vehicle kinematic conditions. This second parameter was addressed by the current study.

Under closed-course conditions, drivers were asked to wait to brake until the last possible moment in order to avoid colliding with the "surrogate" lead vehicle, which was either slowing or stopped. This lead vehicle was designed to mimic a real vehicle as much as possible with the constraint it would allow for safe impacts at low impact velocities. The experimenter had access to add-on brakes and an audible crash alert. Thirty-six younger, 36 middle-aged, and 36 older drivers were tested. Overall, data from over 3,800 last second braking trials were obtained. The critical need for obtaining this type of data under controlled conditions is dictated by the infrequency of near/actual rear-end crashes (and associated "black box" data), the lack of data available to support FCW "benefits" modeling, and the inherent difficulties associated with accident reconstruction.

Converging evidence suggests that the 50th percentile required deceleration value observed in this study under "hard braking" driver instructions appears very promising as an appropriate (not too early/not too late) estimate of the assumed driver braking onset range for crash alert timing purposes. The required deceleration measure was defined, as the constant deceleration level required for the driver to avoid the crash at braking onset. This measure was calculated by using the current speeds of the driver's vehicle and the lead vehicle, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing). To put in another way, the data suggested this required deceleration-based estimate would ensure that, for a high percentage of drivers, the onset of hard braking in response to a crash alert would occur at a closer range than their braking onset range during "aggressive" normal braking, and that this estimate would allow sufficient range for the driver to avoid the crash by hard braking. This required deceleration measure varied with driver speed and lead vehicle deceleration rates, which is in sharp contrast to the "constant (or fixed) driver deceleration level" assumption routinely employed in FCW warning algorithms and "benefits" modeling. It is also important to note that these required deceleration values were relatively uninfluenced by driver age or gender, which is a desirable finding from a production implementation perspective. Additional evidence suggest that drivers with a FCW-equipped vehicle would be capable of executing the observed hard braking levels without exceeding their "comfort zone" for hard braking.

In terms of allowing the driver sufficient warning distances to avoid a crash, 100 meters of sensor "knowledge" accommodated over 90% of drivers in all the various testing conditions, except

when drivers approached a parked vehicle at 60 mph (the highest delta velocity condition tested). There are several caveats associated with this conclusion, including an assumed 1.7 second combined driver perception reaction time plus delay time, that sufficient road surface coefficient of friction is available (dry roads were used here), and that drivers can match the observed hard braking levels during real-world braking in response to a crash alert.

These results also suggest that attempts to define crash alert timing based on research which places drivers under minimal crash risk or no crash risk (e.g., simulator) conditions has potential to lead to overly aggressive crash alert timing. This research approach could in turn lead to the consequence of decreasing the harm reduction potential of the FCW system. In addition, these results raise serious concerns about the real-world validity of previous FCW interface research.

The results of this study were used in the three subsequent driver interface studies for crash alert timing purposes. More specifically, these results, and the subsequent modeling of these Study 1 results (see Appendix A20) aimed at predicting required deceleration values, formed the basis for assumptions regarding the assumed driver deceleration (or braking) behavior in response to the FCW crash alert in the subsequent driver interface studies. These interface studies focused on how to present a crash alert to the driver (i.e., visual, auditory, and/or haptic alerts), and provided an important opportunity to evaluate and validate these deceleration-based crash alert timing approach assumptions.

3.3 Study 1 - “Last-Second” Braking Judgments Without FCW Crash Alerts

3.3.1 Introduction

This research described here is the first of four closed-course, field studies aimed at exploring human factors issues surrounding FCW systems (i.e., the effects of the FCW system and associated interfaces on driver behavior). More specifically, this research will explore human factors issues surrounding FCW which has not been adequately addressed by the relatively limited number of previous human factors studies, which have been conducted either under laboratory conditions (Graham, Hirst, & Carter, 1995; Hirst & Graham, in press) or driving simulator conditions (Janssen & Nilsson, 1990; Janssen & Thomas, 1994; McGehee, Dingus, & Wilson, 1996; Nilsson, Alm, & Janssen, 1991).

The primary goal of this first CAMP study was to develop a crash alert timing approach for a FCW system by exploring a number of performance measures. In this study, a strategy was employed to initially develop a fundamental understanding of the timing and nature of drivers’ “last-second” braking behavior *without* a FCW system, before conducting the subsequent FCW system driver interface studies. This strategy was taken so that drivers’ perceptions of “normal” and “hard braking” kinematic situations could be properly identified and modeled for FCW system crash alert timing purposes. The underlying assumption of this experimental strategy is that properly characterizing (i.e., modeling) the kinematic conditions surrounding these hard braking onsets without FCW system crash alert support will lead to a proper estimate for the

assumed driver deceleration (or braking) behavior in response to a FCW system crash alert across a wide variety of initial vehicle-to-vehicle kinematic conditions.

The three follow-on CAMP human factors studies involve examining driver behavior *with a FCW interface*, in the context of the solid foundation for a crash alert timing approach provided by the present study.

More specifically, in developing a crash alert timing approach for a FCW system, two fundamental parameters involving driver behavior have to be considered. One parameter is the time it takes for the driver to respond to the crash alert and begin braking, referred to as *driver brake reaction time* (or driver brake RT). This parameter was not addressed in the current study, and will be addressed in planned follow-on studies, which will include unexpected braking events. A second parameter involving driver behavior is the assumed braking onset range (which may be expressed either by deceleration-based and/or time-based measures), once the driver has responded to the crash alert and begins to apply the brake. This second parameter was the focus of this study.

Overview of Methodological Approach

Overall, the goal of the current study (and subsequent CAMP studies) is to gather data of the highest real-world validity possible under controlled closed-course conditions. Consistent with this strategic approach, the experimental methodology employed for the current study is aptly described in the following quotation.

> One should not ask subjects to indicate the hypothetical moment they would collide, or the moment an evasive action has to start. Let them perform as if in actual traffic and record when they make their decision and how they react. (van der Horst, 1990, p. 133)

Under closed-course conditions, the current study asked drivers to make last-second braking judgments and maneuvers to a slowing or stopped “surrogate” lead vehicle. This surrogate lead vehicle was designed to mimic a real vehicle as much as possible with the constraint that the surrogate lead vehicle would allow for safe impacts at low impact velocities (up to 10 mph). The passenger-side experimenter had access to add-on brakes and an audible collision alert. Younger, middle-aged, and older drivers were tested. Overall, data from over 3,800 last-second braking trials were obtained. The critical need for obtaining this type of data under controlled conditions is dictated by the infrequency of near and actual collisions in the real-world, the sparseness of “black box” data available during these situations, the lack of data available to support collision warning “benefits” modeling, and the inherent difficulties involved in precisely reconstructing an accident.

3.3.2 Experimental Methodology and Approach

Subjects

Test participants consisted of 18 males and 18 females in each of three different age groups: 20-30 , 40-51, and 60-71 years old. Corresponding mean ages for these younger, middle-aged, and older age groups were 25, 46, and 65 years old, respectively. Each driver was tested individually in one approximately 2 to 2 ½ hour session and paid $150 for their participation. Drivers were recruited by an outside market research recruiting firm, and were required to be within approximately a 45-minute drive from the Milford Proving Ground facility. (Hence, for some participants, the test involved a 4-hour time commitment.) Two drivers, both in the older age group, were not able to complete the test due to feeling uneasy or ill.

Drivers who were ultimately allowed to participate were mailed the information letter shown in Appendix A prior to testing. A copy of the informed consent statement, which describes the various conditions that ruled out potential drivers from participating, is also provided in Appendix A. Participants were required to possess a valid, unrestricted, U.S. drivers license (except for corrective eye glasses), have a minimum of 2 years driving experience, be over 18 years of age, be able to drive an automatic transmission vehicle without assisting devices or special equipment, be able to give informed consent, and not be under the influence of alcohol, drugs, or any other substances (e.g., antihistamines) which may impair their ability to drive. Drivers were also excluded from participation if they had a history of heart condition or prior heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures in the past 12 months, obvious shortness of breath or chronic medical therapy for respiratory disorders, a history of motion sickness, a history of inner ear problems, dizziness, vertigo, or balance problems, diabetes for which insulin is required, chronic migraine or tension headaches, or were pregnant. Additionally, participants were asked to refrain from the use of alcohol, drugs, or any other substances (e.g., antihistamines) which impair their ability to drive for a period of no less than 24 hours prior to participation. Finally, drivers were excluded if anyone in their household worked for an automobile dealer, manufacturer or supplier, an advertising agency, a TV or radio station, a newspaper or magazine publisher, or a market research firm or department.

Test Site

Data was gathered on a 1 mile long, 2 lane wide (12 foot wide lanes), straight, level, smooth asphalt road at the General Motors Milford Proving Ground in Milford, Michigan. The road was closed to all other traffic during testing, and is shown in Figure 3-1. All testing was conducted under daytime conditions under generally dry road and dry weather conditions.

Test Vehicles and the "Surrogate" (Lead Vehicle) Target

Overview of Experimental Apparatus

Test participants were asked to drive behind the lead vehicle, which towed (at about 40 feet behind) a 3-dimensional mock-up of the rear-end of a 1997 Mercury Sable. The driver's (or subject's) vehicle, the mock-up surrogate lead-vehicle, and the lead (tow) vehicle will be subsequently referred to as the *subject vehicle (SV), surrogate target*, and *principle other vehicle (POV)*, respectively. These three elements of the experimental set-up are shown in Figure 3-1 and Figure 3-2. Both the SV and POV were 1997 Ford Taurus SHOs equipped with driver-side airbags and anti-lock brakes. Both the SV and POV were driven by trained Milford Proving Ground test drivers, who were from the General Motors Proving Ground Special Tests Group and had previous experience conducting brake tests. The SV and the POV test drivers communicated during the study via FM radio communication.

Surrogate (Lead Vehicle) Target

The surrogate lead vehicle target was designed to mimic a real vehicle as much as possible with the constraint that, if struck at low speeds (up to 10 mph impact speeds), it would not cause injury to either the test participant or researchers, or damage to the target. Several illustrations of the surrogate target are provided in Figure 3-1 through Figure 3-5. A detailed description of the design of the surrogate target is provided with kind permission from Roush Industries, Inc in Appendix A, at the end of this final report. The basic components of the target include a "skin" made of a flexible polyurethane material, a supporting PVC frame, a trailer assembly (with mild steel tubing), coiled springs attached to a high density foam bumper, a collapsible beam (which could collapse up to 9 feet), working rear lighting, and reflectors (for range sensing purposes).

Figure 3-1 Side View of the Principal Other Vehicle (POV), Surrogate Target (Or Surrogate Lead Vehicle) and Subject Vehicle (SV), as well as an Illustration of the Test Track

Figure 3-2 Side View of the Principal Other Vehicle (POV), Collapsible Beam, Surrogate Target and Subject Vehicle (SV)

Figure 3-3 Close-Up Side View of the Surrogate Target

Figure 3-4 Close-up Rear View of the Surrogate Target

Figure 3-5 Close-up Front View of the Surrogate Target

In order to ensure the safety of the test participants and research team, a surrogate target validation crash impact test was conducted at the GM Safety Test Laboratory where full-scale barrier tests are routinely conducted. The general philosophy of this test was to stage dynamic SV/POV impacts (with the POV stationary) by gradually increasing the SV approach speed until the surrogate target incurred sufficient damage to warrant replacing the target. At this delta velocity (i.e., the difference in speeds between the SV and POV) level, the purpose of the test was to ensure that neither the SV or POV experienced any damage, and that the surrogate target crash impact would not reach the criterion for triggering the driver-side airbag in the SV.

Four crash tests were conducted (in the following order), with impacts of 5.3, 7.5, 10.6, and 10.6 mph, respectively. During the first and fourth test, the SV brakes were not applied. During the second and third tests, only the SV parking brake (i.e., rear brakes) was applied. Results indicated the following. First, the air bag was not activated during any of the four crashes. Second, across tests, only cosmetic SV front bumper damage was obtained, which was the result of the SV hitting a metal vertical plate within the body cavity of the surrogate target, which then pushed the surrogate target forward (which resulted in the collapsible beam collapsing). Across tests, the collapsible beam attaching the POV and surrogate target, which can collapse up to about nine feet, never collapsed more than about 31 inches (about 2 ½ feet). Third, the integrity of the surrogate target remained largely intact across tests. Fourth, there was a tendency for the surrogate target to climb onto the front hood (although it never touched the windshield), particularly at the highest impact speed with no brakes applied. In order to mitigate this tendency, the target was subsequently modified. These modifications involved adding to the rear of the surrogate target a high-density Styrofoam bumper and four coiled springs. In addition, in order to prevent sagging of the target, the target was reinforced with fiberglass in certain areas.

Subsequent “live” surrogate target validation crash tests were performed with a driver and passenger approaching the parked “modified” surrogate target at 5 and 10 mph speeds. These tests resulted in no damage to either the surrogate targets or the test vehicles, and provided strong support that the modifications eliminated any tendency for the surrogate target to climb onto the front hood. In addition, during further pilot testing, the torque of the collapsible beam was loosened up until the point the stability of the surrogate target was not compromised when the POV braked at a -0.45 g deceleration level at the highest test speed (60 mph).

In order to prevent the test participants from experiencing surrogate target impacts above the highest desirable delta velocity, the passenger-experimenter was provided an add-on brake and a “bail-out” FCW crash alert (described later). This alert was used to signal the passenger-experimenter to take over and begin braking. Overall, during formal data collection (i.e., 3,888 last second braking judgment trials), six impacts occurred with the surrogate target. Four of these impacts were relatively minor, and the remaining 2 impacts resulted in the beam collapsing from 1½-2½ feet. Although a spare surrogate target was available, the original target was never replaced during the entire test.

Data Acquisition System

Equipment Overview

The SV and POV were instrumented to continuously record various measures at 30 Hz, including the range (or distance) between the two vehicles, and the speed and acceleration of both test vehicles. All equipment was secured as not to present a hazard. Modifications to the SV included the installation of the following devices: brake pressure sensors (brake pedal load cells), accelerometer, GPS receiver, data logger, inverter, laptop computer, laser radar sensor, video recorder, video splitter, three cameras, and a steering sensor. In addition, a passenger-side override brake pedal, mechanically linked to the driver's brake pedal, was installed on the front passenger's side. Modifications to the POV included the installation of the following devices: brake pressure sensors, accelerometer, GPS receiver, data logger, inverter, laptop computer, smart brake booster, throttle controller, and control for the electric brakes on the trailer. The POV was instrumented such that the POV could automatically brake at a pre-selected constant deceleration value. A rear looking, eye-safe, ranging sensor was also installed on the POV. A conventional trailer hitch was added to the back of the POV, in order to tow the surrogate target. The data logging system, power inverters, and batteries were installed in the trunk and securely fastened to prevent shifting during the testing. A fire extinguisher, first-aid kit, and an FM radio communication system was placed in both test vehicles. A cellular phone was located in the POV.

Software

Data collection and control software was developed using a LABVIEW product. GPS time was used to synchronize the data from both vehicles and the video. Special care was taken to record time on each video frame to synchronize with the data during play back. The user was provided with current information about vehicle performance on the screen of the computer during the testing. The user was able to start and end a test sequence with a single keystroke. The software program was the same for both vehicles. The functions within the program were selectable depending on which vehicle it was used in. A setup file was used to configure the program for the vehicle. The basic differences between the POV and SV functions were the control of braking on the POV, and the control of video recording and audible alert on the SV.

Different POV braking profiles (i.e., constant deceleration profiles) were coded into setup files. The user determined when the profile would be executed for a given test from a single keystroke. The profiles were based on the vehicle speed condition and the POV braking. The software program used the Smart Booster and the accelerometer to control POV braking. The video recorder in the SV was controlled from the same keystroke that started and ended the test. The SV employed information provided by the laser radar sensor function to provide the experimenter an auditory crash alert corresponding to the last possible moment that braking must begin in order to avoid a collision with the surrogate target. The alert algorithm was part of the setup file.

"Bail Out" Crash Alert

The crash alert equation employed was the following (if range was less than the quantity on the right-hand side, the alert was sounded):

$$Range < (((V_{SV}-V_{POV})^2/2(a_{SV}-a_{POV})) + T_{SV}(V_{SV}-V_{POV}))$$

where:
- *V_{SV} and V_{POV} are the measured velocities in m/s of the SV and POV, respectively*
- *a_{SV} is the assumed SV (constant) deceleration value, which was 6.9 m/s^2 (-0.70 g's)*
- *a_{POV} is the assumed POV deceleration based on the trial condition, which was either -1.5, -2.9 m/s^2, - 4.4 m/s^2, (-0.15,-0.30, or -0.45 g's)*
- *T_{SV} is the assumed "travel" delay time value (includes test driver reaction time plus system delay time), which was assumed to be 1 seconds for POV Stationary Trials, and 2 seconds for POV Moving Trials*

Data Recording

All data parameters were recorded at a 30 Hz rate throughout the testing. Data was written to a file in a directory that was unique for that test. The directory names were based on the date and a sequence of run numbers for that day. The folder names were dependent on which vehicle the data was collected, 'RUNAxxx' for the SV and 'RUNBxxx' for the POV. The data was combined from each vehicle at the end of the testing into synchronized files. The combined data was placed into a folder 'RUNCxxx'. The combining process was based on the start and end time of each file for that day. At the beginning of each test, header information was recorded that identified the date, time, vehicle, and setup used.

Procedure and Design

Procedures Before and After Test Trials

After completing various pre-experiment forms and procedures (including the informed consent statement), drivers were escorted to the track. Drivers were then administered test instructions verbally (shown in Appendix A), and asked to adjust the seat, steering wheel, and mirrors to their preferred position, and to fasten their shoulder harness and lap belt.

Before starting testing, a brief review of instructions was again administered verbally (shown in Appendix A). It should be noted that drivers were instructed on the nature of the surrogate target, and more specifically, that this target was designed to allow low speed impacts. Next, a sequence of practice and test trials was conducted, described below. After the test trials were completed, drivers were escorted from the track, debriefed on the purpose of the study, and paid for their participation.

Overview of Test Trials / Driver Instructions

Drivers experienced trials in which the POV was parked (or stationary), and trials in which the POV was moving. These two general types of test trials will be referred to as *Stationary Trials* and *Moving Trials*, respectively. During Stationary Trials, drivers were asked to approach the parked surrogate target at an instructed speed, either 30, 45, or 60 mph. During Moving Trials, drivers followed a lead vehicle which towed the surrogate target at these same three speeds, and were given ample time to maintain and stabilize at what they considered to be their normal following distance. Next, the POV driver enabled the POV to automatically brake to a stop according to a pre-specified braking profile, which resulted in a constant deceleration of either -.15, -.28, or -.39 g's). (It should be noted that the original experimental design called for the two hardest POV braking profile level to be -0.30 and -0.45 g's respectively, but subsequent data analysis indicated that only a POV braking profile levels of -0.28 and -0.39 g's were attained for these two conditions during the study.) At that point, the test participant was asked to wait to brake the SV at the last possible moment in order to avoid colliding with the surrogate target. When both vehicles came to a complete stop, data collection was halted and the trial was ended. During Stationary Trials, drivers were asked to make these same braking judgments while approaching the parked surrogate target.

Drivers were asked to make these last second braking judgments under three different braking instruction conditions, "normal" braking, "comfortable hard" braking, and "hard" braking. Each instruction differed on the instructed braking intensity or pressure. Under one instruction, the driver was asked to brake *with normal braking intensity or pressure*. Under a second instruction, the driver was asked to brake with *the hardest braking intensity or pressure that they felt comfortable*. Under a third instruction, the driver was asked to brake with *hard braking intensity or pressure*. These three instruction conditions were included to provide insight into when drivers should be presented crash alert information, when drivers should not be presented crash alert information (in order to avoid in-path nuisance alerts or any tendency the driver may have to ignore an alert which does in fact signify an alarming situation), and to explore driver's interpretation of "hard braking" and "comfortable hard" braking levels. That is, the use of different braking instructions enabled properly identifying and modeling drivers' perceptions of "normal braking" (albeit "aggressive normal braking") and "hard braking" for crash alert timing purposes.

Drivers were discouraged from "second-guessing" and correcting their initial braking onset judgment by releasing brake pressure (or "double-pumping"), for two reasons. First, even if inaccurate, the interest here is when drivers *perceive* the need to begin braking. Second, it is anticipated that a driver response to a crash alert will typically involve either maintaining or increasing brake pressure (*rather than releasing brake pressure*) throughout the braking maneuver. Hence, it was felt the braking distance and levels observed may be representative of a driver's hard braking levels in response to a crash alert.

Test Trial Sequence

Each driver experienced three blocks of trials, each corresponding to a different braking instruction condition. The first block of trials was always conducted under the normal braking instruction, whereas the second and third block of trials were conducted under comfortable hard and hard braking instructions (with the order of these two braking instructions counterbalanced across drivers). The first block of trials served to get drivers comfortable with braking the vehicle under more normal conditions, and with the "last-second" braking instruction. Trials in which the passenger-experimenter intervened with braking were immediately repeated.

Within each block of trials, drivers experienced 15 trials. During trials 1-3, drivers braked in response to a series of three horizontally aligned traffic cones (placed perpendicular to the vehicle's path of travel). These trials served to get drivers comfortable braking with the vehicle under the last second braking instruction relevant to the block of trials. During trials 4-6, drivers experienced three Stationary Trials, with the order of the three target approach speeds (30, 45, or 60 mph) counterbalanced within a driver's testing session (across the three braking instruction conditions), as well as across drivers. During trials 7-15, drivers experienced nine Moving Trials, formed by crossing the three target speeds (30, 45, or 60 mph) with the three POV braking profile levels (-.15, -.28, or .-39 g's). During these 9 trials, drivers experienced three successive trials at each target speed (each with a different POV braking profile). The order of the three target speeds and the three POV braking profile levels were appropriately counterbalanced within a driver's testing session (across the three braking instruction conditions), as well as across drivers.

Independent Variables Examined

For Stationary Trials, the within-subjects variables analyzed were target speed (30, 45, and 60 mph) and braking instruction (normal, comfortable hard, and hard), and the between-subjects variables were age (younger, middle-aged, or older), gender (male or female), and hard braking instruction order (comfortable hard/hard or hard/comfortable hard). For Moving Trials, the within-subjects variables analyzed were target speed (30, 45, and 60 mph), POV braking profile (-.15, -.28, and -.39 g's), and braking instruction (normal, comfortable hard, and hard), and the between-subjects variables were age (younger, middle-aged, or older), gender (male or female), and hard braking instruction order (comfortable hard/hard, or hard/comfortable hard).

Dependent Measures (Or Performance Measures) Examined

Various performance measures were analyzed for Moving Trials and Stationary Trials. The variable definitions, and the point in time during the braking maneuver in which these measures were analyzed (at POV braking onset, at SV braking onset, throughout the braking, end of the braking maneuver) are shown in Table 3-1.

It should be noted that SV braking onset was <u>not</u> defined relative to the brake switch trigger point, since it was observed that some drivers had a tendency to momentarily ride the brakes during their last-second braking decision. Instead, SV braking onset was defined as the point in

time in which the vehicle actually began to slow as a result of braking. Based on a manual analysis of 10% of the entire data set, SV braking onset was defined as five 30 Hz data samples (or 165 ms) prior to SV crossing the .10 g deceleration level.

The time-to-collision (or TTC) measure was examined under different assumptions about SV and POV deceleration. "*Time-to-collision*" refers to the time it would take for a collision to occur at the prevailing speeds, distances, and trajectories associated with the driver's vehicle and the closest lead vehicle (van der Horst, 1990).

In calculating the TTC during Stationary Trials, the driver's speed at SV braking onset was assumed to remain constant throughout the braking maneuver. That is, this TTC measures provides a measure of the time it would take for drivers to collide (or contact) with the lead vehicle if the drivers continued at their current (or "momentary") speed at SV braking onset.

In calculating the TTC during Moving Trials, two different cases of TTC measures were examined, which made difference assumptions about lead vehicle decelerations. Under TTC-Case 1 (identical to the Stationary Trials case above), this measure was calculated by assuming the current speeds of the driver's vehicle and the lead vehicle. That is, this TTC measures provides a measure of the time it would take for the driver to collide with the lead vehicle if the driver and the lead driver continued at their current speeds.

Under TTC-Case 2 during Moving Trials, this measure was calculated by assuming the current speeds of the driver's vehicle and the lead vehicle, as well as assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing). That is, this measure provides a measure of the time it would take for the driver to collide with the lead vehicle assuming the current speeds of the driver's vehicle and the lead vehicle, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value.

Similar underlying assumptions were made for the required deceleration measure at SV braking onset, which was defined as the constant deceleration level required for the driver to avoid the crash at braking onset. This measure was calculated by using the current speeds of the driver's vehicle and the lead vehicle, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing). It should be noted that in calculating both the TTC and deceleration required measures, the movement state of the lead vehicle (stationary or moving) during the "playing out" of the lead vehicle assumptions (i.e., 0 g deceleration, constant level of deceleration) was addressed.

Table 3-1 Driver Performance Measures Analyzed

Dependent Measure (Measurement Unit)	Variable Definition	Time During Braking Maneuver Which Measure Was Analyzed			
		At POV Braking Onset	At SV Braking Onset *	Through -out Braking	End of SV Braking
SV Speed (mph)	Speed of subject vehicle (SV)		✔		
Initial POV Speed (mph)	Speed of principal other vehicle (POV) at POV braking onset (moving trials only)	✔			
POV Speed (mph)	Speed of POV (moving trials only)		✔		
Delta Velocity (or Delta V in mph)	Difference in speeds between the SV and POV (moving trials only)		✔		
SV Deceleration (g)	Deceleration level of SV		✔		
POV Deceleration (g)	Deceleration level of POV (moving trials only)		✔		
Braking Onset Range (m)	Range (or distance) between the SV and POV at SV braking onset		✔		
Following Headway (sec)	The range between the SV and POV divided by the SV speed at POV braking onset (moving trials only)	✔			
Headway (sec)	The range between the SV and POV divided by the SV speed at SV braking onset		✔		
Time-To-Collision (or TTC in seconds)	The time it would take for the SV and POV to collide under prevailing speeds and assumed deceleration values (see text for 2 cases examined)		✔		
Required Deceleration (g)	The constant deceleration level at braking onset for the SV driver to avoid the crash, assuming the current SV and POV speeds, and that the POV vehicle continues decelerating at the prevailing deceleration value.		✔		
Actual Deceleration(g)	The constant deceleration level needed for the SV to yield the observed stopping distance			✔	
Peak Deceleration (g)	The peak (or maximum) deceleration level reached by the SV driver during the braking maneuver			✔	
Braking Distance (m)	SV stopping or braking distance			✔	
Minimum TTC (sec)	The minimum TTC value reached by the SV during the braking maneuver			✔	
Minimum Headway (sec)	The minimum time headway reached by the SV during the braking maneuver (moving trials only)			✔	
Minimum Range (m)	The minimum range between the SV and the POV reached during the braking maneuver			✔	
End Range (m)	The range between the SV and the POV when the SV has come to a full stop				✔

Note: * SV braking onset was defined relative to when the vehicle actually began slowing rather than by the brake switch trigger point.

3.3.3 Results and Discussion

Overview of Statistical Analysis Approach

A mixed factorial Analysis of Variance (ANOVA) was performed for each performance measure defined in Table 3-1. Data from Stationary Trials and Moving Trials were analyzed separately during the statistical analysis. For Stationary Trials, the within-subjects variables analyzed were target speed (30, 45, and 60 mph) and braking instruction (normal, comfortable hard, and hard), and the between-subjects variables were age (younger, middle-aged, or older), gender (male or female), and hard braking instruction order (comfortable hard/hard or hard/comfortable hard). For Moving Trials, the within-subjects variables analyzed were target speed (30, 45, and 60 mph), braking instruction (normal, comfortable hard, and hard), and POV braking profile (-.15, -.28, and -.39 g's), and the between-subjects variables were age (younger, middle-aged, or older), gender (male or female), and hard braking instruction order (comfortable hard/hard or hard/comfortable hard). This ANOVA approach was used to explore underlying relationships between the various independent variables and performance measures. Due to the exploratory nature of this research and the relatively large number of statistical tests carried out (which increases the probability of spuriously significant results, (Hays, 1981)), the criterion set for statistical significance was $p<0.01$. Statistically significant effects are shown for Stationary Trials in Table 3-2, and for Moving Trials in Table 3-3. All statistically significant results indicated in these tables at least met (and often exceeded) the adopted $p<0.01$ criterion.

It should be stressed that this analysis was considered a necessary precursor to a modeling activity aimed at predicting SV driver range at braking onset for crash alert timing purposes in planned follow-on studied examining FCW interfaces. Hence, rather than explaining and giving equal emphasis to every statistically significant effect observed (which is shown for Stationary Trials in Table 3-2, and for Moving Trials in Table 3-3), the following discussion and data presentation is more focused around the goal of determining a crash alert timing approach.

In this vein, the performance measures in Table 3-1, which will not be discussed here in any great detail, include the effects involving the braking instruction and POV braking profile variables on the following measures (all measured at SV braking onset): SV speed, SV deceleration, POV speed, and POV deceleration. In general, these effects were extremely small in magnitude and of negligible practical significance. In any case, these effects will be addressed in the subsequent modeling of these data, which will attempt to develop equations for predicting driver's braking onset range in the current study. However, one important effect involving the POV braking profile variable was actually an experimental manipulation, and indicated that the three POV braking profiles corresponded to -.15, -.28, and -.39 g's, respectively. In addition, "isolated" higher-order interaction effects, which were not generally observed across measures (i.e., Table 3-2, rows 9-10; and Table 3-3, rows 12-13 and 15-18), will not be discussed here. Once again, these effects were generally small in magnitude.

Table 3-2 Stationary Trials Data - Overview of Statistically Significant Effects (*p< .01, **p< .001, ***p< .0001)

		At Braking Onset					Throughout Braking			End of Braking Range
Ref. Row	**Significant Effects**	**Speed**	**Decel.**	**Range**	**TTC**	**Req. Decel.**	**Actual Decel.**	**Peak Decel.**	**Min. TTC**	
1	Age			*	*	*			*	*
2	Gender					*				
3	Order									
4	Braking Instr.		***	***	***	***	***	***	***	*
5	Speed	***	***	***	***	***	***	***	***	***
6	O x BI			*	*	***	**	***	**	*
7	A x Sp									**
8	BI x Sp			***	**		***	**	*	*
9	A x O x Sp	*								*
10	O x BI x Sp								*	

Note: For rows 6-10 above, A=Age, O=Hard Braking Instruction Order, BI=Braking Instruction, and Sp=Speed.

Table 3-3 Moving Trials Data – Overview of Statistically Significant Effects (*p< .01, **p< .001, ***p< .0001)

		At POV Braking Onset		At SV Braking Onset										Throughout Braking						End of SV Braking
Ref. Row	**Significant Effects**	**Time Head -way**	**Initial POV Speed**	**SV Speed**	**SV Dec.**	**POV Speed**	**POV Dec.**	**Delta V**	**Range**	**Time Head -way**	**TTC (Case 1)**	**TTC (Case 2)**	**Req. Dec.**	**Actual Dec.**	**Peak Dec.**	**Min. TTC (Case 1)**	**Min TTC (Case 2)**	**Min. Head -way**	**Min. Range**	**End Range**
1	Age																			
2	Gender																			
3	Order																			
4	Braking Instr.	***		***	*	***	***	***	***	***	***	***	***	***	***	***	***	***		
5	Speed	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
6	Braking Prof.			***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
7	O x BI												*	*	***					
8	G x Sp																			
9	BI x Sp			*			**		***		*	***	*				**			
10	BI x BP			***			***		**	**	***	***	***	***	***	***	***	***	***	***
11	S x BP							*	***			***	***	***	*	**	***		***	***
12	O x BI x BP												***							
13	O x Sp x BP													***						
14	BI x Sp x BP													***					***	*
15	G x BI x BP														*					
16	A x G x Sp		*																	
17	A x G x BI x BP															*				
18	A x BI x Sp x BP																			**

Note: For rows 7-18 above, A=Age, G=Gender, O=Hard Braking Instruction Order, BI=Braking Instruction, Sp=Speed and BP=Braking Profile. During The two different cases of TTC measures examined (TTC-Case1 and TTC-Case 2) are described in the text.

Driver's Compliance to Speed Instruction and Headway Instructions

Before discussing the effects of each independent variable on the various performance measures, it is important to verify that drivers followed the experimenter instructions prior to their initiation of last-second braking. Drivers were instructed to maintain 30, 45 or 60 mph speeds. In addition, during Moving trials, drivers were instructed to follow at their normal following distance.

Results shown in Table 3-4 indicate that both the SV (and POV) were very close to target speeds during both Stationary Trials and Moving Trials. Results from Table 3-5 indicate that the average time headway observed across age groups in the current study (at POV braking onset) correspond closely to those recently observed in the manual (no adaptive cruise control) condition in the recent large-scale ACC field trials (Sayer, Fancher, Ervin, and Melford, 1997). (It should be noted that, in the current study, the effect of the age variable on this average time headway measure only reached a $p<0.10$ level of statistical significance.) This latter result provides strong evidence that drivers' time headways during Moving Trials in the current study are representative of real-world driving conditions, and were not altered by the last-second braking judgment task.

Hard Braking Instruction Order Effects

Although there were no main effects of the hard braking instruction order variable (see row 3 of Table 3-2 and Table 3-3), this variable interacted with the hard braking instruction order variable in a robust fashion during Stationary Trials (see Table 3-2, row 6), and for a few measures during Moving Trials (see Table 3-2, row 7). A representative example of this Hard Braking Instruction Order x Braking Instruction interaction is shown in Figure 3-6 for the average required deceleration measure during Stationary Trials. (This measure will be shown shortly to be a key measure for crash alert timing purposes.) This interaction indicates that during the first and third block (or set) of trials, the average required deceleration values were no different across hard braking instruction order conditions (comfortable hard/hard *versus* hard/comfortable hard). However, during the second block of trials, average required deceleration values were higher for the "hard/comfortable hard" hard braking instruction order group relative to the "comfortable hard/hard" order group. This pattern of results suggests that drivers in the latter group may have been relatively more aggressive in their third block of trials due to experiencing the "hard braking" instruction in the previous block of trials. In any case, the magnitude of this interaction effect (.02 g's) was relatively small for this measure, as well as other performance measures analyzed. Furthermore, it is interesting to note that data were more stable in the "hard" relative to "comfortable hard" braking instructions across the two hard braking instruction orders, which suggests that the driver's interpretation of "hard" braking is relatively insensitive to practice. This insensitivity to practice would seem to make data from the hard braking instruction condition a better candidate for modeling crash alert timing, particularly if drivers with a FCW-equipped vehicle are instructed that "hard" braking may be one of the appropriate responses to a crash alert. Overall, as will be shown below, the data from the comfortable hard braking instruction condition are nearly identical to that obtained in the hard braking instruction

condition. This would suggest that drivers with a FCW-equipped vehicle would be capable of executing the hard braking levels observed in the current study without exceeding their "comfort zone" for hard braking. Finally, as can be seen by examining the significant interaction effects in Table 3-2 (rows 6-10) and Table 3-3 (rows 7-18), the braking instruction order variables did not generally interact across with other performance measures.

Age and Gender Effects

The only significant main effects of either age or gender occurred during Stationary Trials (see rows 1-2 of Table 3-2 and Table 3-3), when drivers experienced the highest delta velocity (and perhaps the highest perceived risk) levels. The main effects of age during Stationary Trials are shown in Table 3-6, and indicate the younger group behaved more aggressively than the middle-aged and older group, with largely no difference in behavior between the two older groups. A main effect of gender was found during Stationary Trials for only the average required deceleration measure, and indicated average required deceleration values of -.29 and -.31 g's for female and male drivers, respectively. Overall, it should be noted that main effects of age and gender are relatively small in magnitude. In addition, as can be seen by examining the significant interaction effects in Table 3-2 (rows 6-10) and Table 3-3 (rows 7-18), the age and gender variables did not generally interact with the more "kinematic-oriented" variables of speed, braking instruction, and POV Braking profile across performance measures. Hence, to the extent to which one would want to add a correction factor in crash alert timing to accommodate differences in either age and/or gender, the process is seemingly very straightforward, <u>and</u> the underlying relationships between the more kinematic-oriented variables (which will now be discussed) still hold.

Table 3-4 Comparison of Speed Instructions Versus Driver's Actual Speeds at the Time of Critical Braking Events

	POV Stationary Trials	POV Moving Trials	
Speed Instruction	**Average SV Speed at SV Braking Onset**	**Average SV Speed at SV Braking Onset**	**Average POV Speed at POV Braking Onset**
Maintain 30 mph	29.8	30.3	30.3
Maintain 45 mph	44.6	45.9	45.9
Maintain 60 mph	58.0	60.8	60.8

Table 3-5 Comparison of Time Headways During CAMP Moving Trials Versus UMTRI ACC Field Trials Across Age Groups

	Average Time Headways (sec)	
Age Group*	**CAMP at POV Braking Onset**	**UMTRI ACC Field Trials (Sayer et al., 1997)**
Young	1.3	1.2
Middle	1.6	1.4
Old	1.6	1.5

* The young, middle-aged and older groups in the current study were defined as 20-30, 40-51, and 60-71 years old, respectively. In the UMTRI ACC Field Trials (Sayer et al., 1997), the corresponding age groups (which are nearly identical) were 20-30, 40-50, and 60-70 years old, respectively.

Table 3-6 Effects of Age on Various Performance Measures During Stationary Trials

	At Braking Onset				
Age Group	**Ave. Range (m)**	**Ave. TTC (sec)**	**Ave. Req. Decel. (g)**	**Ave. Min TTC (sec)**	**Ave. End Range (m)**
Young	69.2	3.4	-.31	2.0	7.5
Middle	78.9	3.8	-.29	2.5	12.1
Old	79.1	3.8	-.28	2.4	11.1

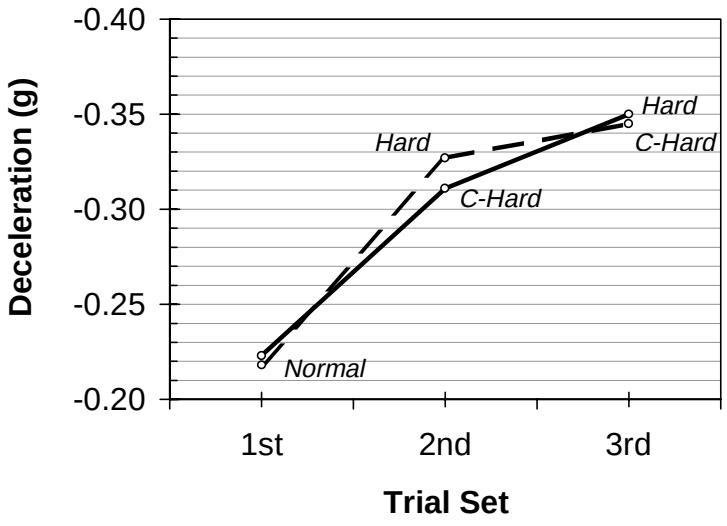

Figure 3-6 Average Required Deceleration at Braking Onset as a Function of Trial Set and Braking Instruction During Stationary Trials

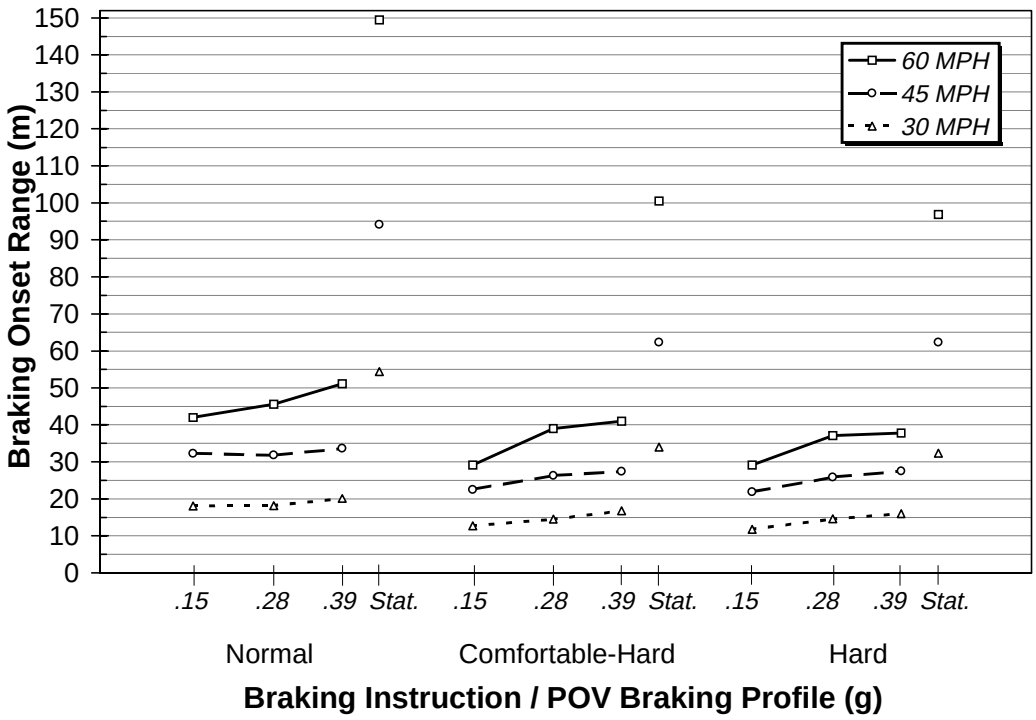

Figure 3-7 Average Range at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

Speed, Braking Instruction and POV Braking Profile Interaction Effects: "Kinematic Figures"

Developing the "Kinematic Figure" concept

The following discussion is aimed at providing the reader a close look at the various higher-order interactions observed between the kinematic-oriented variables across performance measures. These variables play a paramount and fundamental role in determining appropriate crash alert timing. For Stationary Trials, these key kinematic-oriented variables include speed and braking instruction. For Moving Trials, these key kinematic-oriented variables include speed, braking instruction, and POV braking profile.

These kinematic-oriented variables provided robust main effects across performance measures during Stationary Trials (see Table 3-2, rows 4 and 5) and Moving Trials (see Table 3-3, rows 4-6). In addition, these key kinematic-oriented variables strongly interacted with one another. During Stationary Trials, this can be observed in the robust Speed x Braking Instruction interaction (see Table 3-2, row 8). Similarly, during Moving Trials, this can be observed in the Braking Instruction x Speed interaction (see Table 3-3, row 9), Braking Instruction x Braking

Profile interaction (see Table 3-3, row 10), and the Speed x Braking Profile interaction (see Table 3-3, row 11).

Hence, a data presentation approach which focuses on the highest-order interaction between kinematic-oriented variables provides the most powerful approach for interpreting the underlying trends of this large data set, and allowing the reader to make clean, straightforward comparisons across performance measures. For Stationary Trials, the highest-order interaction between kinematic-oriented variables is provided by the Speed x Braking Instruction (2-way) interaction. For Moving Trials, the highest-order interaction between kinematic-oriented variables is provided by the Speed x Braking Instruction x POV Braking Profile (3-way) interaction. Furthermore, in order to facilitate comparisons between data obtained during Stationary Trials and Moving Trials for a given performance measure, data from the corresponding "highest order" interactions under these two types of trials are presented on the same figure. For ease of terminology purposes, this type of figure will subsequently referred to as a "*Kinematic Figure*". For some measures, it should be noted that Stationary Trials data is not shown on the Kinematic Figure, primarily because the measure is not appropriate for these types of trials. Finally, to the extent possible, Kinematic Figures corresponding to similar performance measures are grouped together.

An example of a Kinematic Figure described above, which represents a key strategy for representing and interpreting this large data set, is shown in Figure 3-7 for the average range at SV braking onset measure. In each of these Kinematic Figures, the performance measure is shown on the vertical axis, and the various combinations of the braking instruction/POV braking profile conditions are shown on the horizontal axis. Note that for illustrative purposes, the Stationary Trials condition is represented as a POV braking profile level. Furthermore, the various lines/connecting points on the figure correspond to the three different speed conditions under each braking instruction/POV braking profile combination, with isolated non-connected points used to represent the Stationary Trials data. It should be noted that 108 drivers (with occasional outliers removed) contributed to each of the 36 data points shown on any given Kinematic Figure. In total, each Kinematic Figure represents data from approximately 3,888 last second braking judgment trials.

In interpreting these Kinematic Figures, it is useful to point out that data from the normal braking condition is less aggressive than that obtained from the hard and comfortably hard braking conditions. Also, the data from the comfortable hard braking instruction condition is nearly identical to that obtained in the hard braking instruction condition. (As was mentioned earlier, this latter finding would suggest that drivers with a FCW-equipped vehicle would be capable of executing the observed braking levels in the current study without exceeding their "comfort zone" for hard braking.) Hence, in analyzing these Kinematic Figures with an eye toward thinking about crash alert timing, the reader may find it advantageous to focus on data from the hard braking instruction condition (the rightmost third of the figure), which provides additional rationale for the "Kinematic Figure" approach. Indeed, data from the hard braking instruction condition will be the focus of much of the following discussion. The importance of data from the normal braking instruction condition and its relevance to driver annoyance (i.e., in-path nuisance alerts) will be primarily discussed later when examining percentile data. Next, a brief discussion

will be provided of each of the Kinematic Figures corresponding to various performance measures.

Delta V

The Kinematic Figure corresponding to the average difference in velocities (or delta V's) between the SV and POV at SV braking onset is shown in Figure 3-8. Although the data from Stationary Trials is not shown in this figure (since it would triple the size of the vertical scale, and diminish the readers ability to see the pattern of results during Moving Trials), the reader should know that the delta velocities during Stationary Trials simply correspond to the driver's speeds at SV braking onset. These latter speeds corresponded very closely to drivers' instructed speeds (see Table 3-4). Under the hard braking instruction conditions during Moving Trials, the average delta velocities ranged from 8-16 mph. As can be seen in Figure 3-8, overall, the delta V's increased as the (instructed) speeds increased and as the lead vehicle (POV) braked harder. This pattern of results is generally true across measures, many of which are highly correlated. It is also interesting to note that the 85th percentile delta V's ranged from 13-26 mph across the hard braking instruction conditions.

Peak Decelerations

The Kinematic Figure corresponding to the average peak deceleration of the SV throughout the braking maneuver is shown in Figure 3-9. Across all hard braking instruction conditions, the average peak deceleration values ranged between -.75 and -.90 g's. During Stationary Trials, the average peak decelerations remained relatively constant across approach speeds. In contrast, during Moving Trials, the average peak deceleration values increased as speeds increased from 30 mph to the two higher speeds (45 mph and 60 mph), and increased as the POV braked harder.

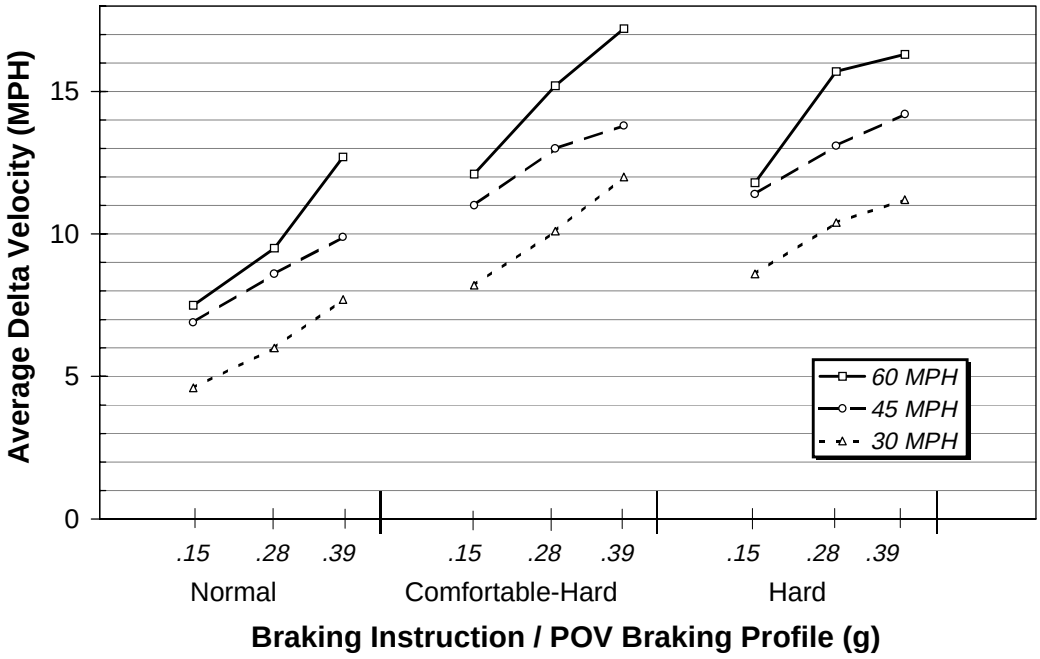

Figure 3-8 Average Differences in Velocities (Delta V) Between the SV and POV at SV Braking Onset During Moving Trials as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

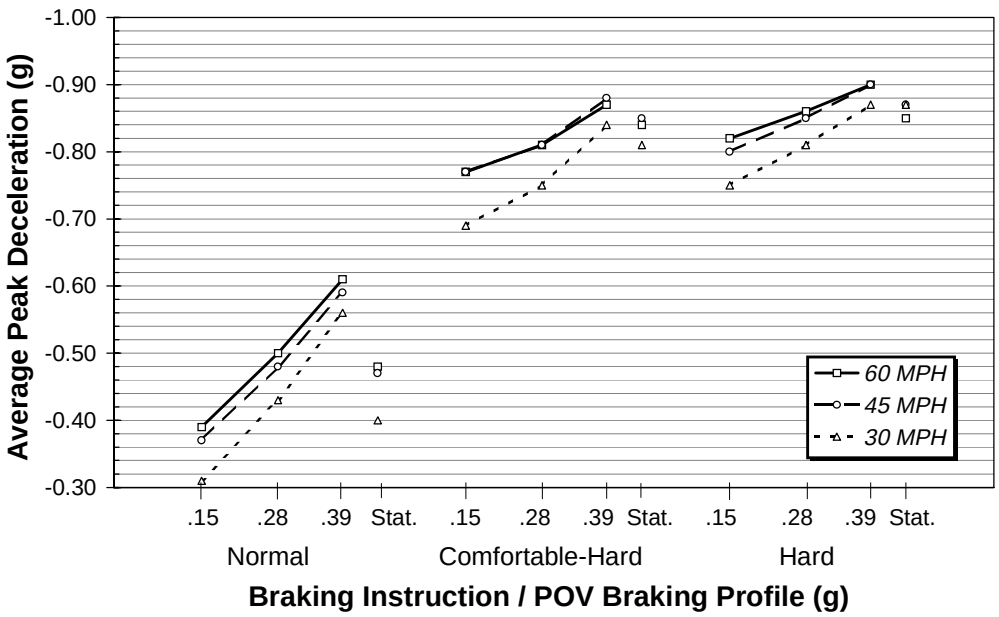

Figure 3-9 Average Peak Deceleration of the SV Throughout Braking as a Function of Braking Instruction, POV Profile, and Speed Condition

Range at Braking Onset / Exploring Sensor Range Requirements

The Kinematic Figure corresponding to the average range between the SV and POV at SV braking onset is shown in Figure 3-7. This figure indicates that, overall, the average range at SV braking onset increased as speeds increased and as the lead vehicle (POV) braked harder. This figure clearly illustrates that in terms of determining requirements for FCW sensor range, situations corresponding to the Stationary Trials condition (e.g., a parked vehicle) will demand substantially longer driver warning distances than situations corresponding to Moving Trials.

Figure 3-10 examines the Stationary Trials data in terms of exploring potential requirements for driver warning distances (and hence, FCW sensor ranges). In this figure, a 1.7 second travel distance (based on observed speeds in the three different speed conditions) is added to three following measures; average stopping distance, average range between the SV and POV at SV braking onset, and 90th percentile stopping distances. (These latter stopping distances can be viewed of as long, or conservative.) The 1.7 seconds value is based on an assumed 1.5 second percentile P-RT, and an additional 0.2 second system delay time (which included the time it takes for the vehicle to begin slowing after the brakes are applied). The assumed driver P-RT time corresponds to an 85th-95th percentile driver perception-response time value (Olson, 1996), which is a percentile range commonly used in traffic engineering. (The reader can easily explore other assumed P-RT values by converting the assumed driver P-RT to a travel distance across the three speeds, and adding this distance to the measures provided in Figure 3-10.)

As can be seen in Figure 3-10, the 100 meters of “sensor knowledge” accommodates the proposed potential driver warning distances for avoiding a crash in the 30 and 45 mph speed condition (for 90% of drivers in the 45 mph condition), but falls short in the 60 mph condition. It should be stressed that substantial collision mitigation would still be possible in this latter speed condition. It should also be noted that the above conclusions assume that drivers will at least match the observed hard braking levels in the current study under real-world conditions in response to a crash alert, and that the road surface coefficient of friction can support the hard braking levels observed in the current study (which may not be true under wet, snowy, or icy road surface conditions).

Braking Distance

Although this measure was not statistically analyzed (since it is redundant with the average deceleration measure), the Kinematic Figures corresponding to SV braking distance is shown in Figure 3-11. As can be seen in this figure, overall, the average braking distances increased as speeds increased and decreased as the lead vehicle braked harder. It is also interesting to note that the across the three speed conditions under both comfortable hard and hard braking instruction conditions, braking distances found during Stationary Trials correspond closely to those found during Moving Trials in the -.28 g POV braking profile condition .

Minimum Range / End Range

The Kinematic Figures corresponding to the average minimum range throughout braking and the average end range are shown in Figure 12 and Figure 13, respectively. Note that these two variables are equivalent during Stationary Trials, and that these data are redundantly displayed in both of these two Kinematic Figures. During Moving trials, these two variables are not necessarily identical, since the minimum range can occur during the actual braking maneuver. Both Figure 12 and Figure 13 indicate that, overall, both the average minimum range and average end range increased as speeds increased, and decreased as the lead vehicle braked harder. For the hard braking instruction condition during Stationary Trials, the average minimum range (or equivalently, average end range) shown in Figure 13 increased approximately 1-3 mid-size car lengths in a fairly linear fashion as target speeds increased from 30-60 mph. The definition used here of a mid-size car length is 5.1 m, which corresponds to the length of a Chevrolet Lumina or Ford Taurus. Interestingly, this same pattern of results was true for the minimum range measure during Moving Trials for the hardest POV braking profile condition (-.39 g). Overall, these results would appear to suggest that a driver’s preferred “buffer zone” increased with driver speed.

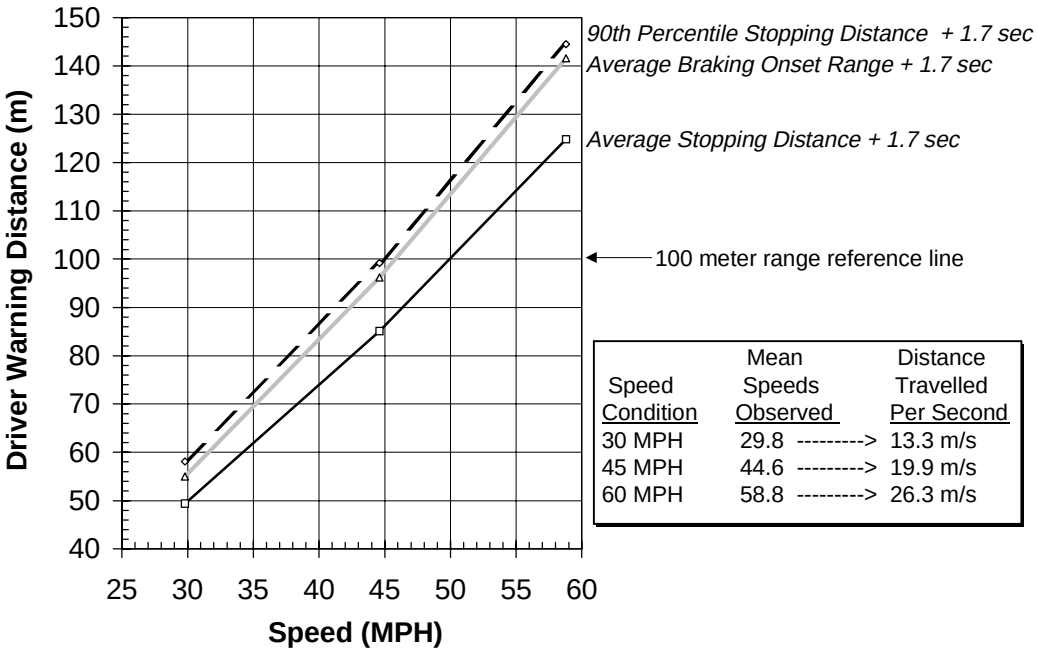

Figure 3-10 Potential "Driver Warning" Distances Based on Adding 1.7 Seconds Travel Distance to the Following Measures in the Hard Braking/Stationary Trials Conditions: Ave. Braking Onset Range, Ave. Stopping Distance, and the 90th Percentile Stopping Distance

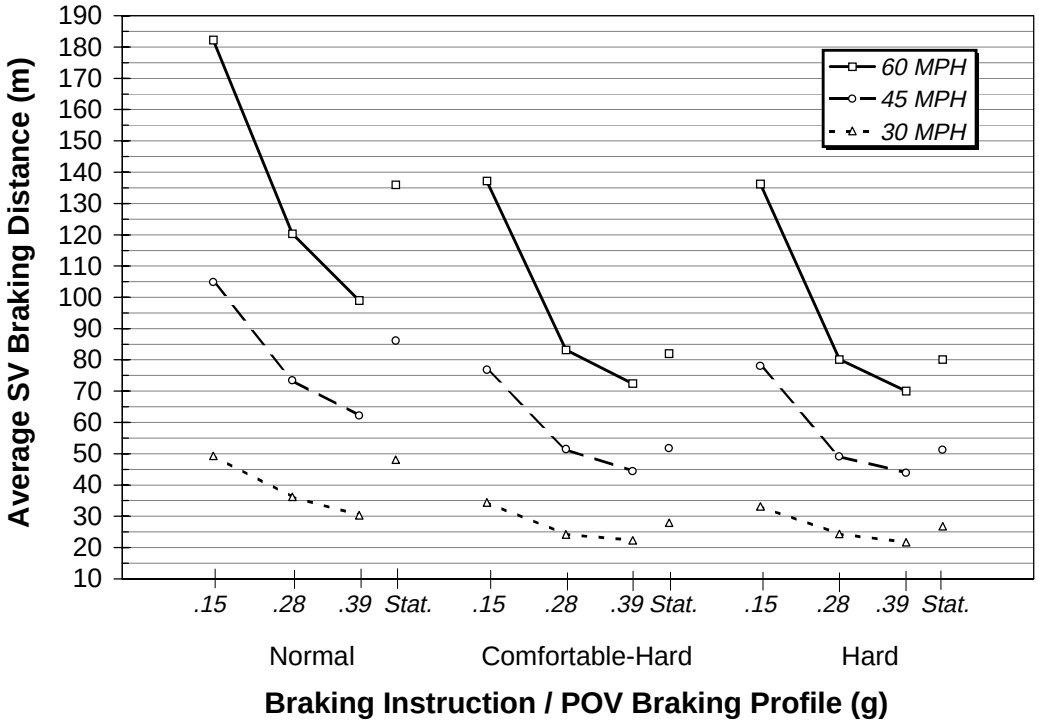

Figure 3-11 Average SV Braking Distance as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

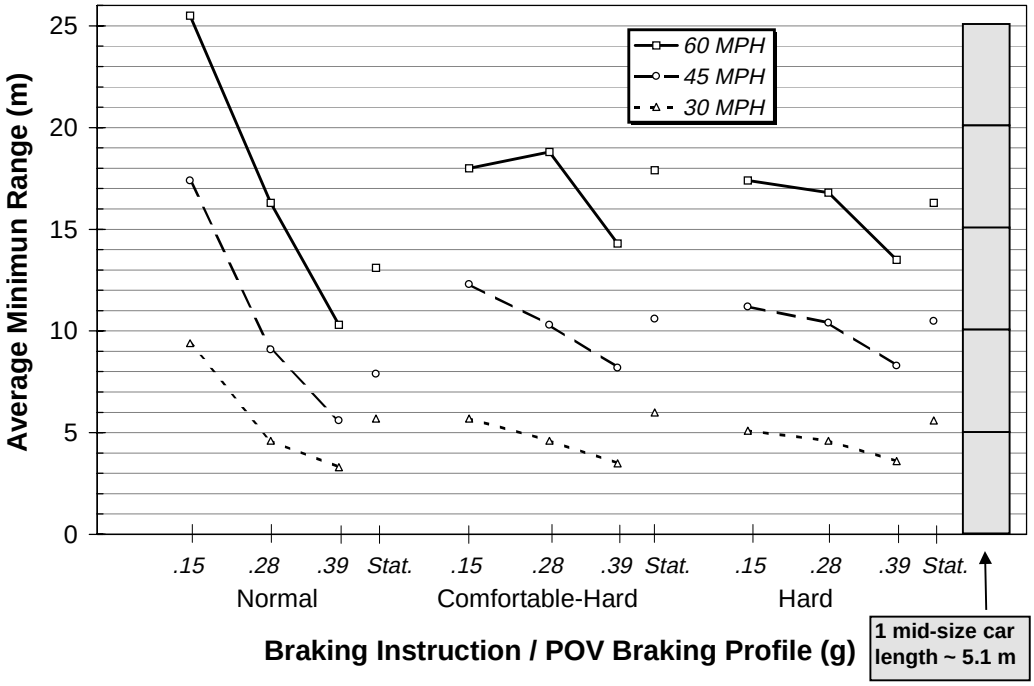

Figure 3-12 Average Minimum Range Throughout Braking as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

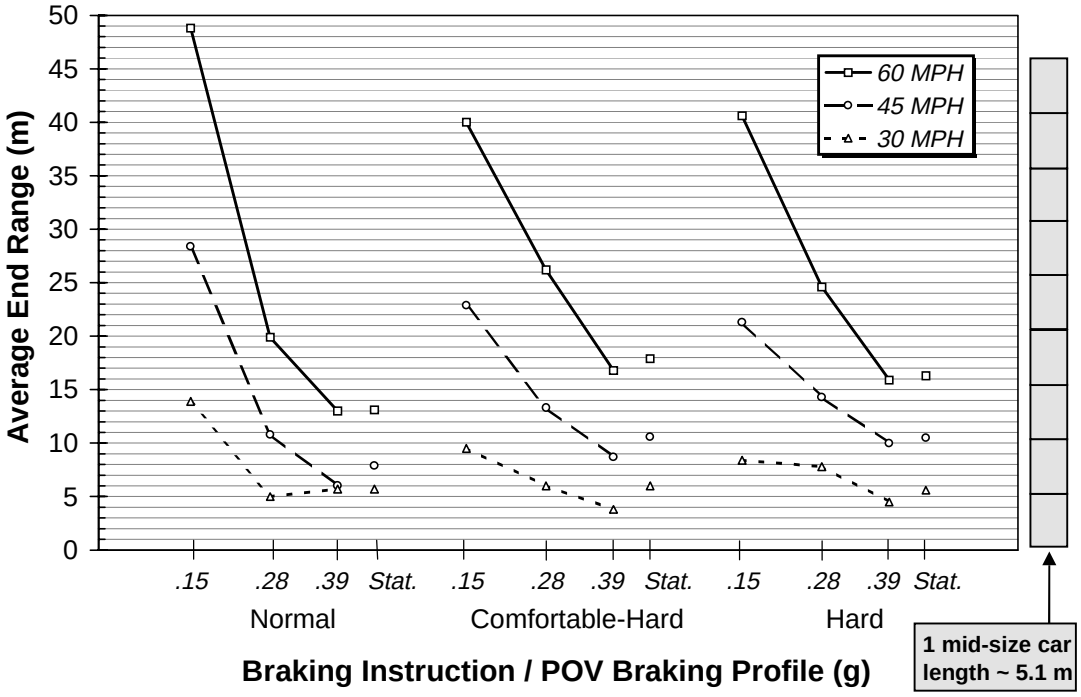

Figure 3-13 Average End Range as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

However, the interpretation of these minimum range and end range data are not straightforward, since (as discussed above in the "Procedure and Design" section) drivers were discouraged from "second-guessing" and correcting their initial braking onset judgment by releasing brake pressure (or "double-pumping"). Hence, this constraint *may* have resulted in higher (more conservative) end ranges and/or higher minimum ranges than may have been obtained if drivers were given the opportunity to release pressure off the brakes during the brake maneuver. This hypothesis will be further tested in the two follow-up closed course studies, which will not constrain the driver's braking behavior in this manner, and will also include unexpected braking events.

Actual Deceleration and Required Deceleration

Before discussing the results from the actual deceleration and required deceleration measures, which will be argued to be the most important variables examined here for developing a FCW crash alert timing approach, it is important to elaborate on the definitions of these variables provided earlier in Table 3-1. Figure 3-14 provides an illustration of the definition of these measures for the Stationary Trials condition. Referring to Figure 3-14, the reader is to imagine the vehicle shown on the left is approaching the parked vehicle shown to the far right, and then begins braking, and eventually comes to a stop. The top illustration depicts the case where the driver's braking distance enables the driver to avoid colliding with the lead vehicle by a few car lengths. The braking distance observed could than be re-expressed as the constant (or fixed) deceleration level needed to yield the actual (observed) stopping distance, defined as the *actual deceleration* measure. Now imagine replaying this same exact sequence of events, except the driver comes to a stop right at the front bumper of the lead vehicle. The "hypothetical" braking distance observed can than be re-expressed as the constant (or fixed) deceleration level required for the driver to avoid the crash at braking onset, defined as the *required deceleration* measure. Note that assuming the driver avoids the crash, the actual deceleration value is always greater than the required deceleration value. However, the exact relationship between the actual and required deceleration measures is in no way predetermined or inherently straightforward. That is, the relationship between these measures may be different across drivers, as well as for any given driver across different vehicle-to-vehicle kinematic conditions.

Data from both the actual and required deceleration measures under Stationary Trials conditions is shown in Figure 3-15. For both measures, this figure reveals only small differences between the comfortable hard and hard braking conditions, and a consistent (approximately .07 g) difference or "tight coupling" between the actual and required measures. Furthermore, both measures increased as the driver's speed increased (i.e., people braked harder at higher speeds). The Kinematic Figures corresponding to the actual and required deceleration measures (which also include the Stationary Trials data shown in Figure 3-15) are shown in Figure 3-16 and Figure 3-17, respectively. As was found during Stationary Trials, during Moving Trials, these two figures reveal only small differences between the comfortable hard and hard braking conditions, and a consistent difference or "tight coupling" between the actual and required deceleration measures (this effects can be better observed by overlaying transparencies of each of these two figures). Furthermore, both measures increased as the lead vehicle braked harder. For two hardest POV braking profile conditions (-.28 and -.39 g's) during Moving Trials, both the actual and required deceleration measures increased as the driver's speed increased (i.e., people

braked harder at higher speeds), particularly at the hardest POV braking profile condition (-.39 g's). However, for the least aggressive POV braking profile condition (-.15 g's), both the actual and required deceleration measures remained stable across driver speeds.

Overall, and in sharp contrast to commonly proposed crash alert timing approaches, these results suggest that it may be advantageous to vary the assumed driver deceleration value for crash alert timing as a function of driver speed and lead vehicle deceleration. Across the entire range of experimental conditions tested under the hard braking instruction condition, the average required deceleration values ranged from -.22 to -.45 g's (as can be seen in Figure 3-17). This range can be compared to the driver deceleration values assumed in the early phase of CAMP program (prior to Human Factors testing), which assumed fixed -.3 and -.5 g values for the driver's response to cautionary and imminent crash alerts, respectively.

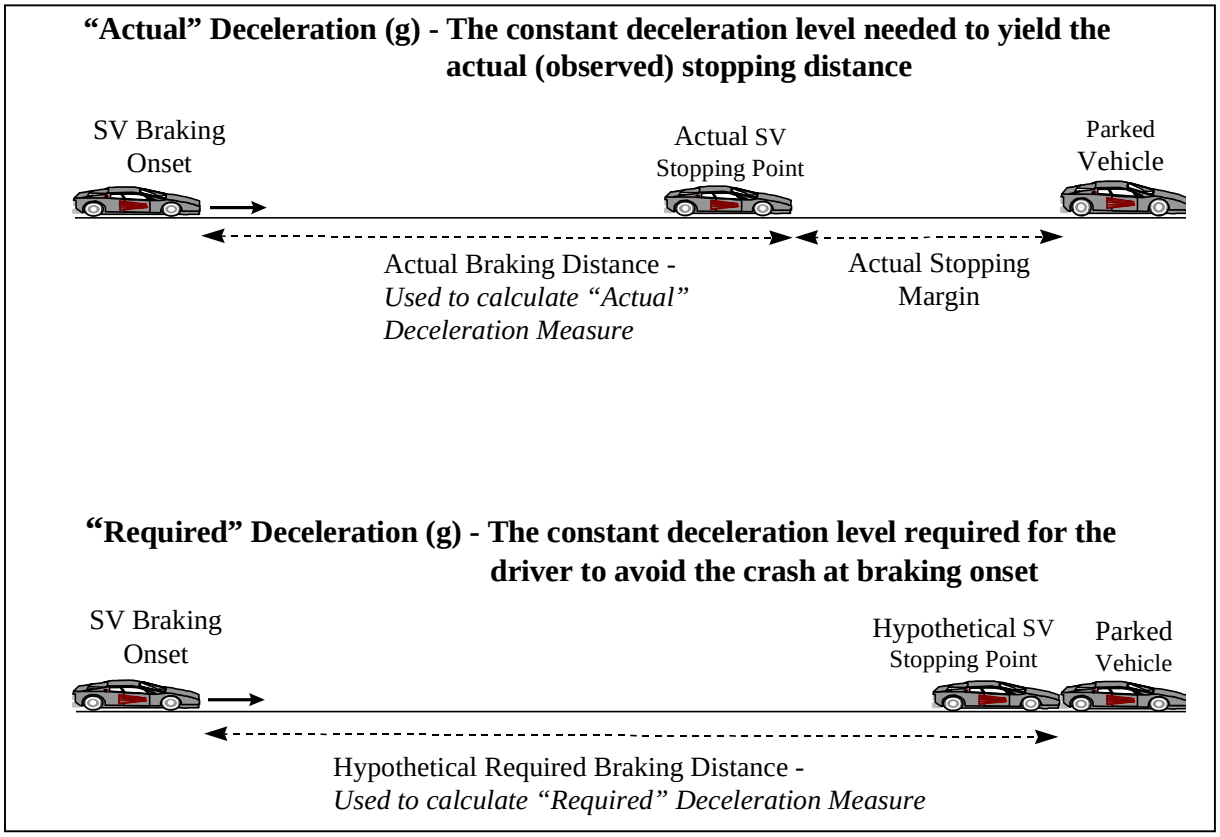

Figure 3-14 Definition of "Actual" Deceleration and "Required" Deceleration Measures (Illustrated for Case Where Lead Vehicle is Stationary or Parked)

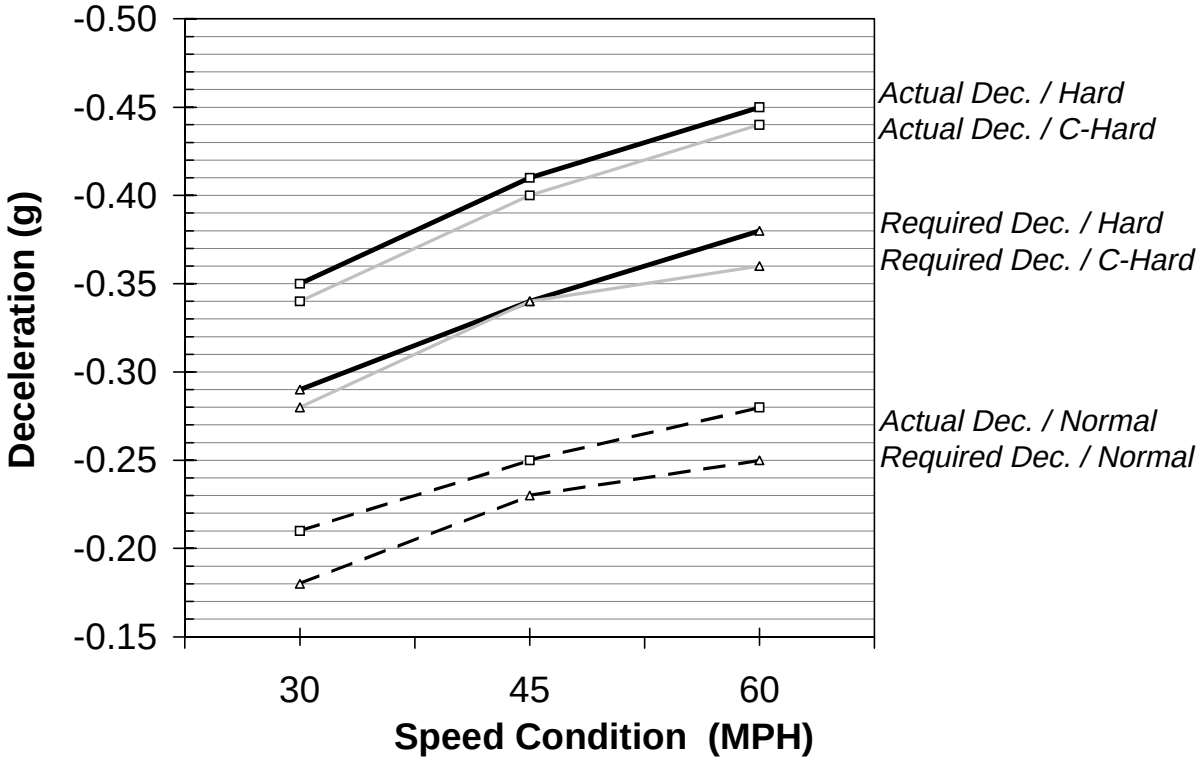

Figure 3-15 Average "Required" Deceleration and Average "Actual" Deceleration Values as a Function of Speed Condition and Braking Instruction for the Stationary Trials

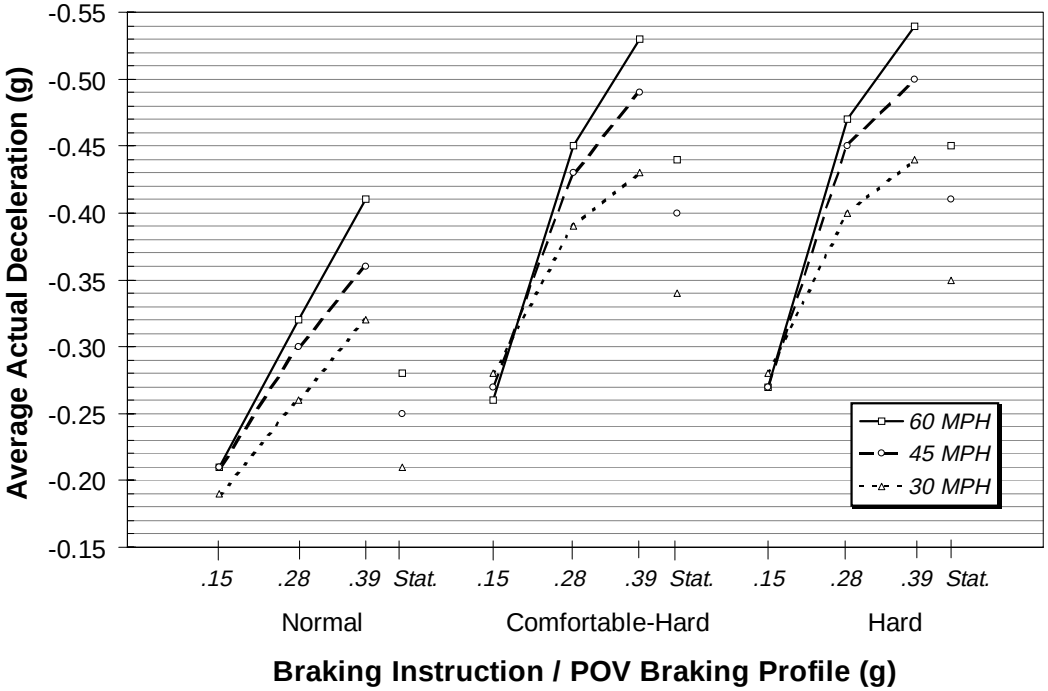

Figure 3-16 Average "Actual" Deceleration of SV as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

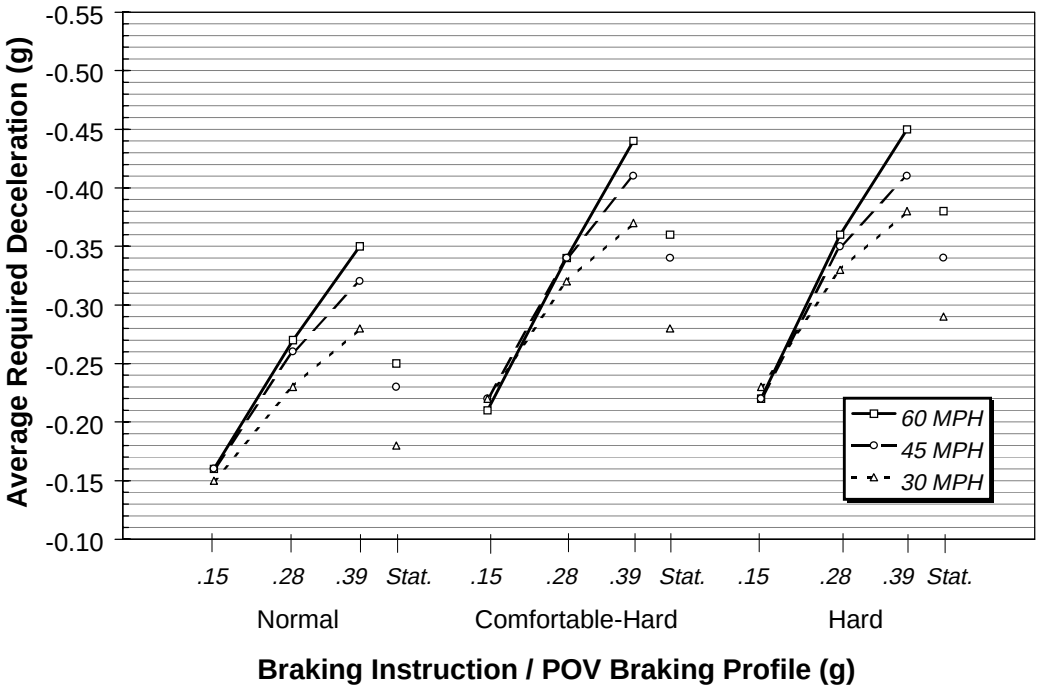

Figure 3-17 Average "Required Deceleration of SV at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

Actual and Required Deceleration: Promising Measures for Developing a Crash Alert Timing Approach

As was touched upon earlier, the actual deceleration and required deceleration measures appear to be the most important variables of all those examined here for developing a crash alert timing approach, for two primary reasons.

First, the required deceleration measure appears to be tightly coupled to a fundamental kinematic variable, braking or stopping distance (re-expressed here in terms of an actual deceleration measure). The time-based measures (TTC or headway), which will be discussed soon, do not provide a direct linkage to a fundamental kinematic variable.

Second, a "stability" analysis of performance measures across experimental conditions suggests that the required deceleration measure remain more stable (in terms of either central tendency or data spread measures) than either the actual deceleration measure or any of the time-based measures examined at SV Braking Onset (i.e., TTC-Case 1, TTC-Case 2, time headway). To the extent that a measure is stable across experimental conditions for a given driver, and that measure's stability is consistent across drivers, the measure offers two important advantages. First, the measure may come closer to matching the underlying criterion drivers use for deciding when to brake and how hard to brake. Second, the measure may eliminate (or at least mitigate) the need for a crash alert criterion control, which is a desirable feature from a production implementation and a simplicity/ease of use perspective.

This "stability" analysis is shown in Table 3-7 and Table 3-8 for Stationary Trials and Moving Trials, respectively, and involves calculating *coefficients of variation* (*COV*). The COV is defined for a given measure as the standard deviation divided by the mean (standard deviation/mean). This measure allows the distinct advantage of comparing across measures on the same "normalized" scale. Each table entry of Table 3-7 and Table 3-8 is based on 108 separate COV measures, with each driver contributing a single COV measure based on all the trials experienced under comfortable hard and hard braking conditions (i.e., 6 trials under Stationary Trials conditions and 18 trials Moving Trials conditions).

For each COV measure shown in the left-hand column of Table 3-7 and Table 3-8, a measure's stability is reflected by low values. The measures corresponding to the central tendency of the COV (i.e., average, median) provide a measure of the extent to which the measure remains stable across experimental conditions for a given driver. During Stationary Trials, paired t-tests revealed significantly lower mean COV values for the required deceleration measure relative the TTC-Case 1 measure ($p < 0.0001$), with no difference found between the actual and required deceleration measure. During Moving Trials, paired t-tests revealed significantly lower mean COV values for the required deceleration measure relative to the TTC-Case 1 measure ($p < 0.0001$), with no difference found between the required deceleration measure and the actual deceleration, TTC-Case 2, and time headway measures.

The measures in the left-hand column of Table 3-7 and Table 3-8 corresponding to the variation or spread of the COV measure (i.e., standard deviation, minimum value, and maximum value)

provide a measure of the extent to which a measure's stability across experimental conditions for a given driver is consistent across drivers. Hence, in this case, a measure's stability is reflected by low COV standard deviations, low COV minimum values, and low COV maximum values. During Stationary Trials, overall, the required deceleration measure shows lower values across these measures of COV variability relative to the actual deceleration and TTC-Case 1 measures. During Moving Trials, overall, the required deceleration measure shows lower values across these measures of COV variability relative to the actual deceleration and the time-based measures examined at SV Braking Onset (i.e., TTC-Case 1, TTC-Case 2, time headway). It is worthwhile noting that the time headway measure appears surprisingly stable relative to the TTC measures.

Hence, in addition to the "tight coupling" observed between the required deceleration measure and the actual deceleration measure, this COV "stability" analysis provides further supports further for exploring the required deceleration measure for crash alert timing purposes. Another fruitful avenue for exploring the required deceleration measure for crash alert timing purposes is to examine percentile values, which is a common practice in traffic engineering (e.g., using 85th-95th percentile values for design purposes). Table 3-9 and Table 3-10 provides the data which is the basis for an argument that the 50th percentile required deceleration value during hard braking may be a well-founded assumption for the assumed driver deceleration in response to a crash alert. In making this argument, it is best to start by examining a "nominal" experimental condition in the study, which is during Moving Trials where the instructed speed was 45 mph and the lead vehicle braked at -.28 g's. Percentile data for this nominal condition is shown in Figure 3-18. The arguments made below for this specific experimental condition hold equally well for the remaining experimental conditions, which will be discussed shortly (and is supported by data from Table 3-9 and Table 3-10).

The left-most percentile curve in Figure 3-18 represents data for the required deceleration measure under the normal braking instruction condition. As can be seen by the vertical dotted line on this figure, more than 96% of all (108) drivers exhibited required deceleration values of approximately -.35 g's or *less*. Put in another way, only 4% of drivers exhibited required deceleration values of approximately -.35 g values or *more* in the normal braking instruction condition.

The middle percentile curve in Figure 3-18 represents data (once again) for the required deceleration measure, but this time under the hard braking instruction condition. As can be seen by the vertical dotted line on this figure, the 50th percentile required deceleration value under the hard braking instruction is approximately -.35 g. Hence, coupling this curve with the left-most percentile curve suggests that assuming the 50th percentile required deceleration value observed during hard braking for crash alert timing (i.e., the assumed driver deceleration in response to a crash alert) would be unlikely to annoy drivers doing "normal" braking (via an in-path nuisance alert). This is particularly true if the assumption is made that the observed required deceleration values during the normal braking instruction condition are more "aggressive" than corresponding values during normal "real-world" braking, largely because the "normal" braking in this study was performed in the context of a last-second braking instruction.

Table 3-7 Coefficients of Variation (COV) Within-Subjects for Select Performance Measures Relevant for Crash Alert Timing Purposes During *Stationary Trials* (COV=Standard Deviation/Average)

	Performance Measure at SV Braking Onset		
Coefficient of Variation Measure	**Required Deceleration (g)**	**Actual Deceleration (g)**	**TTC-Case 1 (sec)**
Average	0.16	0.17	0.22
Median	0.16	0.16	0.22
Standard Deviation	0.05	0.07	0.06
Minimum Value	0.06	0.07	0.10
Maximum Value	0.30	0.70	0.35

Note: Each table entry above is based on 108 separate COV measures (one per driver), with each driver contributing a single COV measure based on 6 Stationary Trials. These 6 trials correspond to the 3 "comfortable hard" braking instruction trials and the 3 "hard" braking instruction trials, where the 3 trials in each of braking instruction condition correspond to the 3 speed condition levels.

Table 3-8 Coefficients of Variation (COV) Within-Subjects for Select Performance Measures Relevant for Crash-Alert Timing Purposes During *Moving Trials* (COV = Standard Deviation/Average)

	Performance Measure at SV Braking Onset				
Coefficient of Variation Measure	**Required Deceleration (g)**	**Actual Deceleration (g)**	**TTC-Case 1 (sec)**	**TTC-Case 2 (sec)**	**Time Headway (sec)**
Average	0.29	0.29	0.35	0.28	0.28
Median	0.29	0.29	0.33	0.28	0.27
Standard Deviation	0.04	0.08	0.11	0.06	0.07
Minimum Value	0.16	0.16	0.18	0.17	0.13
Maximum Value	0.41	0.74	1.00	0.52	0.48

Note: Each table entry above is based on 108 separate COV measures (one per driver), with each driver contributing a single COV measure based on 18 Moving Trials. . These 18 trials correspond to the 9 "comfortable hard" braking instruction trials and the 9 "hard" braking instruction trials, where the 9 trials in each of braking instruction condition are formed by the crossing of the 3 speed condition levels by the 3 POV Braking Profile levels.

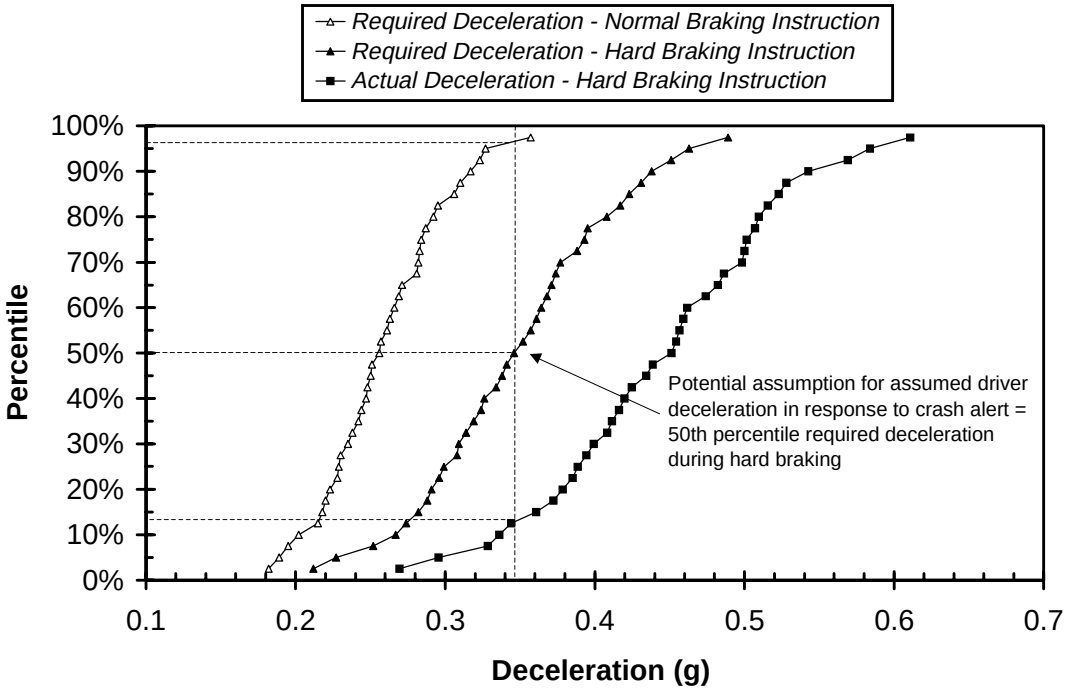

Figure 3-18 Percentile Values for the "Required" and "Actual" Deceleration Measures During Moving Trials for the 45 mph/-0.28 g POV Braking Profile Condition

Table 3-9 Exploring the Utility of Deceleration-Based Measures for Crash-Alert Timing Purposes with *Stationary Trials* Data

			Speed Condition		
Braking Instr. Cond.	**Deceleration Measure**	**%tile**	**30 mph**	**45 mph**	**60 mph**
Normal	Required Deceleration	95th	-.27	-.32	-.35
Hard	Required Deceleration	50th	-.29 (-.29)	-.34 (-.34)	-.38 (-.38)
Hard	Actual Deceleration	15th	-.28	-.34	-.36

Note: Values in parentheses indicate corresponding mean values. Also, it should be stressed that Study 1 normal braking can be considered on the aggressive side of normal braking.

Table 3-10 Exploring the Utility of Deceleration-Based Measures for Crash Alert Timing Purposes with *Moving Trials* Data

			Speed Condition (mph) / POV Braking Profile Condition (g)								
Braking Instr. Cond.	**Deceleration Measure**	**%tile**	**30 / -.15**	**30 / -.28**	**30 / -.39**	**45 / -.15**	**45 / -.28**	**45 / -.39**	**60 / -.15**	**60 / -.28**	**60 / -.39**
Normal	Required Deceleration	95th	-.20	-.30	-.37	-.20	-.33	-.42	-.21	-.34	-.45
Hard	Required Deceleration	50th	-.23 *(-.23)*	-.33 *(-.33)*	-.38 *(-.38)*	-.22 *(-.22)*	-.35 *(-.35)*	-.41 *(-.41)*	-.21 *(-.22)*	-.36 *(-.36)*	-.45 *(-.45)*
Hard	Actual Deceleration	15th	-.22	-.31	-.36	-.22	-.36	-.41	-.21	-.39	-.45

Note: Values in parentheses indicate corresponding mean values. Also, it should be stressed that Study 1 normal braking can be considered on the aggressive side of normal braking.

The next important question to ask is whether drivers would be capable of braking to avoid the crash if the 50th percentile required deceleration value observed during hard braking was used as the assumed driver deceleration in response to a crash alert. The right-most percentile data curve in Figure 3-18 represents for the actual deceleration values under the hard braking instruction. As can be seen by the vertical dotted line on this figure which passes through the 50th percentile required deceleration values data under the hard braking instruction, the actual deceleration values for 13% of drivers fall to the left of this line, which suggest that for these drivers the 50th percentile required deceleration value (during hard braking) is too aggressive for allowing them to avoid the crash (although collision mitigation may occur). On the other hand, for approximately 87% of the drivers, the 50th percentile required deceleration value during hard braking accommodates the actual deceleration values observed during hard braking. If it is assumed that drivers will in fact brake harder (if required) under real-world condition than observed in the current study, than the 15% of the drivers not accommodated by the 50th percentile required deceleration value during hard braking would be substantially reduced or eliminated. This would in effect move the rightmost percentile curve in Figure 3-18 farther to the right.

Corresponding data for the remaining experimental conditions are shown in table form in Table 3-9 for Stationary Trials and Table 3-10 for Moving Trials. (These two tables also reinforce the point made above that the required deceleration measures are a function of both driver speed and lead vehicle deceleration.) For each experimental condition (including the nominal condition discussed at length above), three percentile values are provided:

- The *95th* percentile *required deceleration* value under *normal braking* conditions.
- The *50th* percentile *required deceleration* value under *hard braking* conditions.
- The *15th* percentile *actual deceleration* value under *hard braking* conditions.

The pattern of results in Table 3-9 for Stationary Trials and in Table 3-10 for Moving Trials provide strong evidence that the arguments made above for nominal 45 mph / -.28 g condition during Moving Trials (shown in middle part of Table 3-9) hold equally well for the remaining experimental conditions.

First, across experimental conditions during both Stationary Trials and Moving Trials, the 95th percentile required deceleration value observed under normal braking instruction conditions virtually never exceeds (with one exception) the 50th percentile required deceleration value observed under hard braking instruction conditions. Assuming a 50th percentile required deceleration value during hard braking for crash alert timing (i.e., the assumed driver deceleration in response to a crash alert), would be unlikely to annoy drivers doing “normal” braking particularly if the assumption is made that the required deceleration values during the normal braking instruction observed in this study are more aggressive than corresponding values during normal real-world driving.

Second, across experimental conditions during both Stationary Trials and Moving Trials, the 50th percentile required deceleration value observed under hard braking instruction conditions is remarkably close to the 15th percentile actual deceleration value observed under hard braking

conditions. Hence, for approximately 85% of the drivers, the 50th percentile required deceleration value during hard braking accommodates the actual deceleration values observed during the hard braking instruction condition. If it is assumed that drivers will in fact brake harder (if required) under real-world conditions than observed in the current study, than the remaining approximately 15% of the drivers not accommodated by this approach may be substantially reduced or eliminated.

Hence, overall, assuming the 50th percentile required deceleration value during the hard braking condition for the assumed driver deceleration in response to a crash alert appears promising. First, it appears that only a relatively small percentage of drivers (less than 5%) would find this assumed SV driver deceleration response to be not aggressive enough. However, if one assumes the normal braking levels observed here are more aggressive than in the real world, this small percentage of drivers may be reduced or eliminated. Second, it appears that only a relatively small percentage of drivers (less than 15%) would find this assumed SV driver deceleration value too aggressive. (It should be noted that these drivers may experience some level of collision mitigation). However, if one assumes that drivers could in fact brake harder (if required) under real-world conditions relative to those here, this relatively small percentage of drivers may be reduced or eliminated. This assumption will be further tested in two follow-up closed course studies, which will also include unexpected braking events.

In any case, the 50th percentile required deceleration value observed during hard braking appears to provides a solid anchor and foundation for assumptions surrounding the assumed driver deceleration in response to a crash alert. More generally, in terms of estimating driver's maximum braking capabilities, it is interesting to note that the highest (i.e., most aggressive) 15th percentile actual deceleration value across experimental conditions was -.45 g's (see bottom rows of Table 3-9 and Table 3-10). This "highest" value occurred during Moving Trials in the 60 mph /-.39 POV braking profile condition.

Time-Based (Headway and TTC) Measures

For the reasons discussed in detail above, the time-based measures examined at SV Braking Onset (TTC-Case 1, TTC-Case 2, and time headway) do not appear as promising as deceleration-based measures for developing FCW crash alert timing. Briefly, these reasons included the lack of a direct linkage of time-based measures to a fundamental kinematic variable (e.g., braking distance), and the finding (via a "stability" covariance analysis) that the required deceleration levels (or values) remain more stable than any of the time-based measures examined at SV braking onset (i.e., TTC-Case 1, TTC-Case 2, time headway).

However, given the large amount of previous work examining these time-based measures (see van der Horst (1990) for a review of this work), the interested reader is provided Kinematic Figures for each of the time-based measures defined in Table 3-1 in Figure 3-19 through Figure 3-24. The reader should note that for Stationary Trials, the time-based measures at SV braking onset (i.e., time headway, TTC-Case 1, and TTC-Case 2.) are equivalent, and redundantly provided on each of these Kinematic Figures for comparative purposes. It should also be noted that the minimum

TTC values observed during the braking maneuver have been previously interpreted as a measure of the imminent danger of a collision during the braking maneuver (van der Horst, 1990).

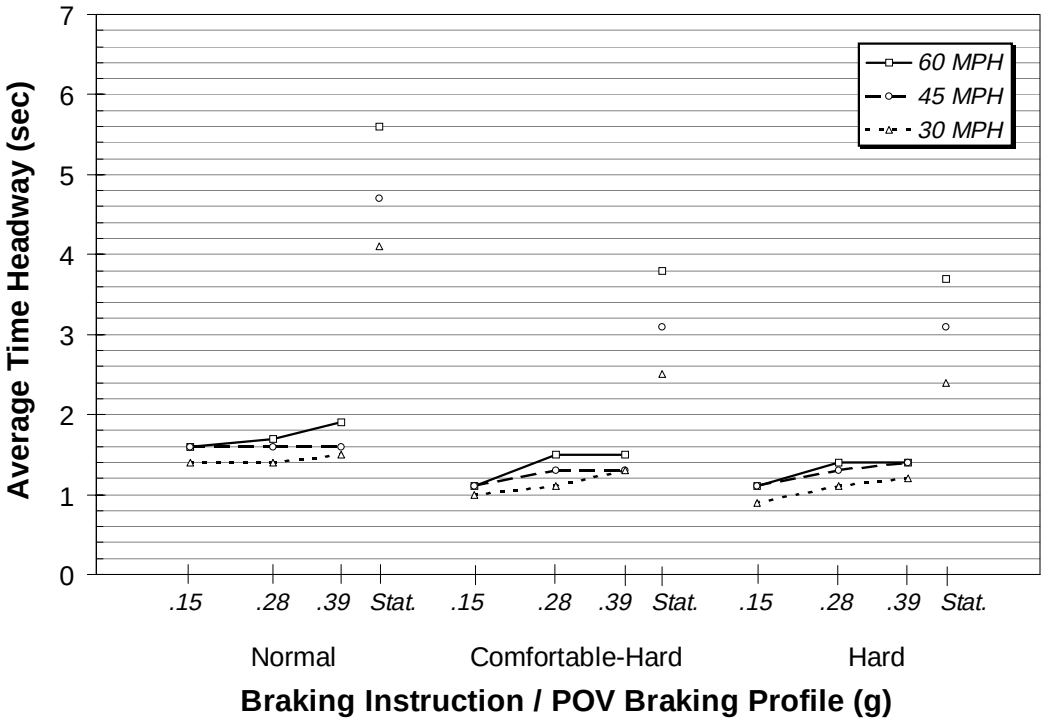

Figure 3-19 Average Time Headway at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

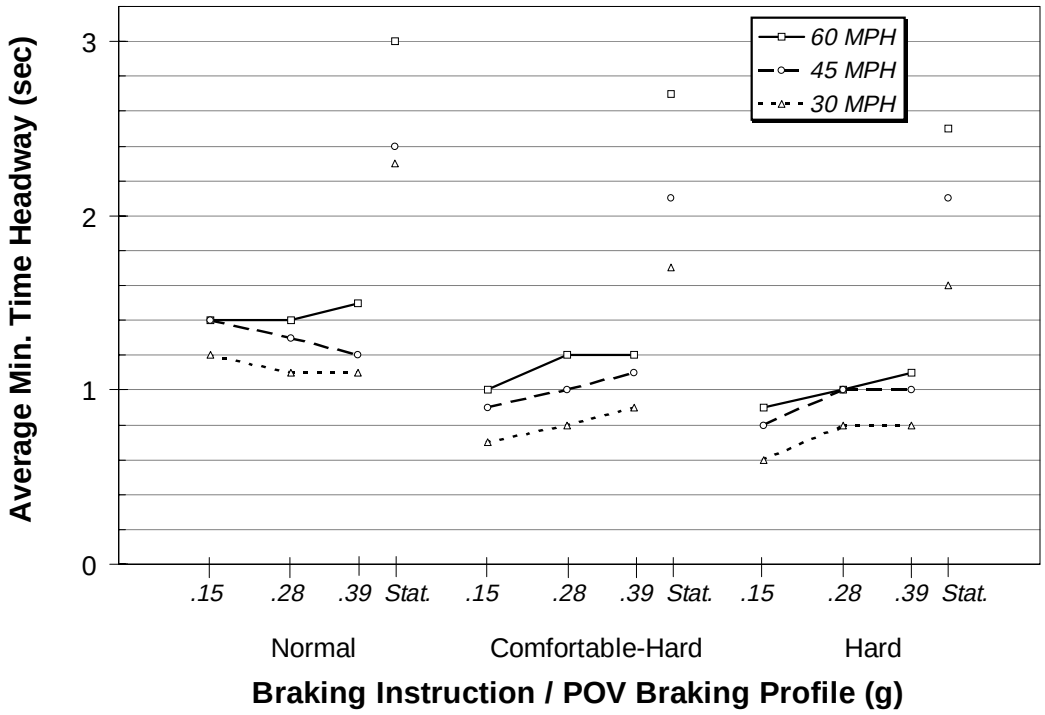

Figure 3-20 Average Minimum Time Headway Throughout Braking as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

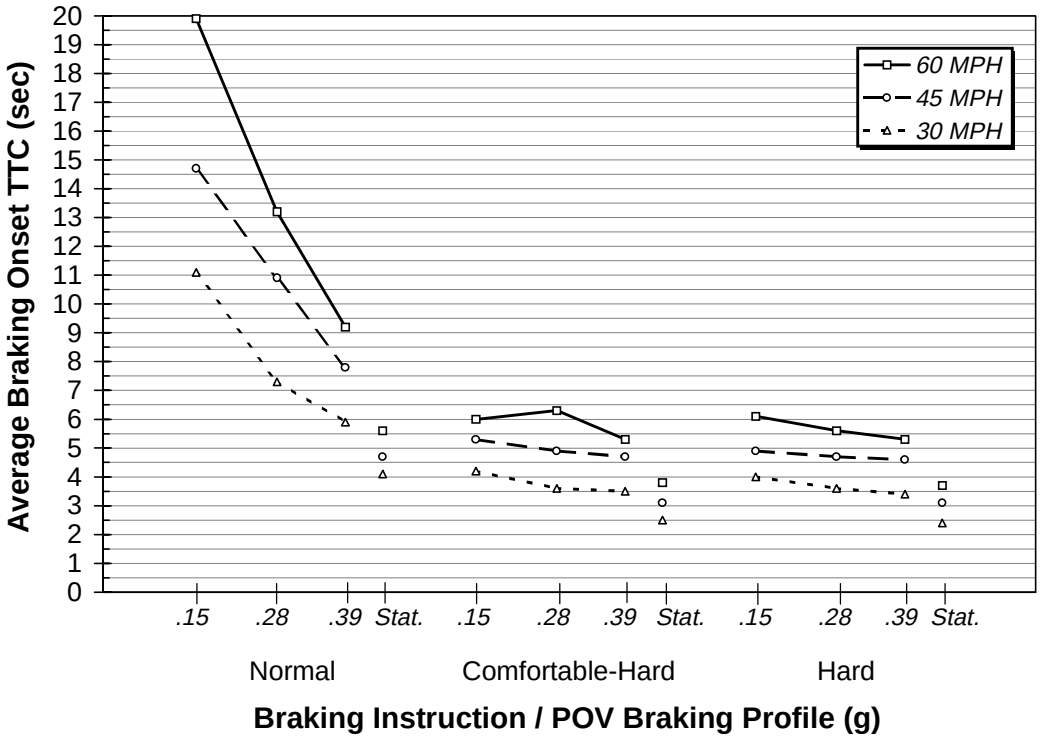

Figure 3-21 Average TTC (Case 1) at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

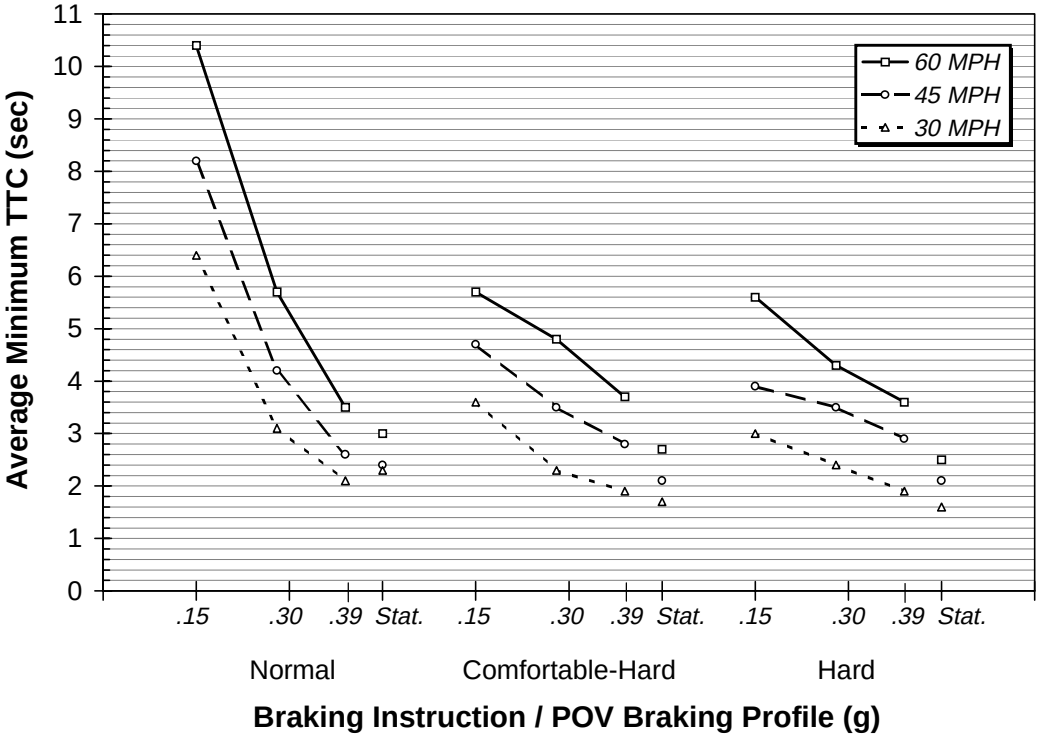

Figure 3-22 Average Minimum TTC (Case 1) Throughout Braking as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

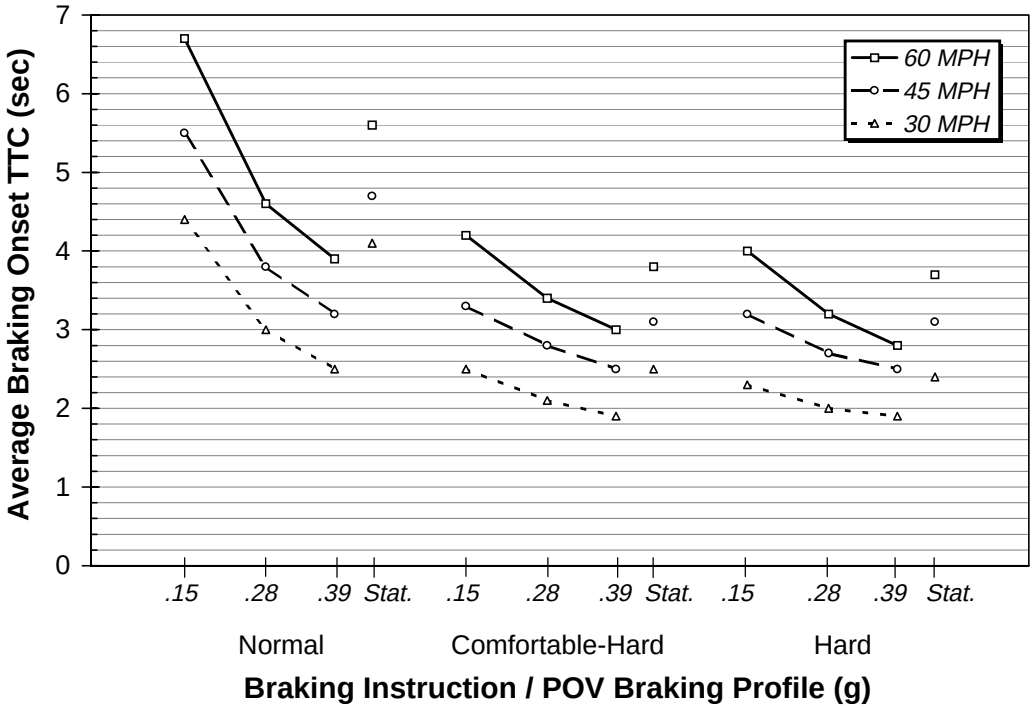

Figure 3-23 Average TTC (Case 2) at SV Braking Onset as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

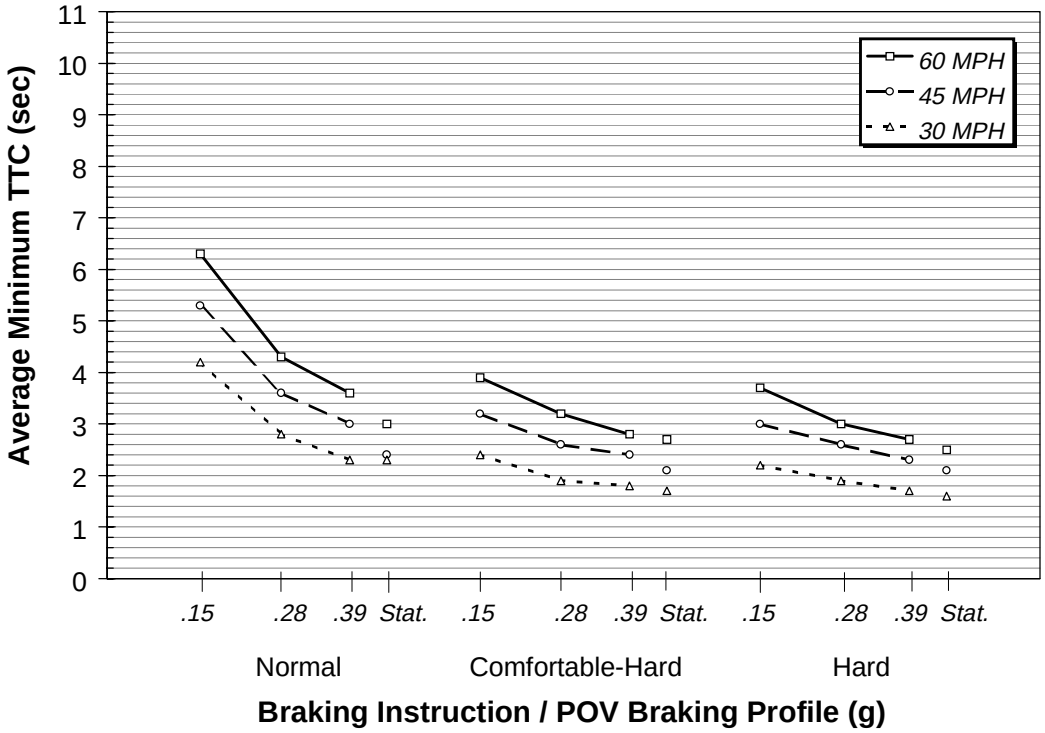

Figure 3-24 Average Minimum TTC (Case 2) Throughout Braking as a Function of Braking Instruction, POV Braking Profile, and Speed Condition

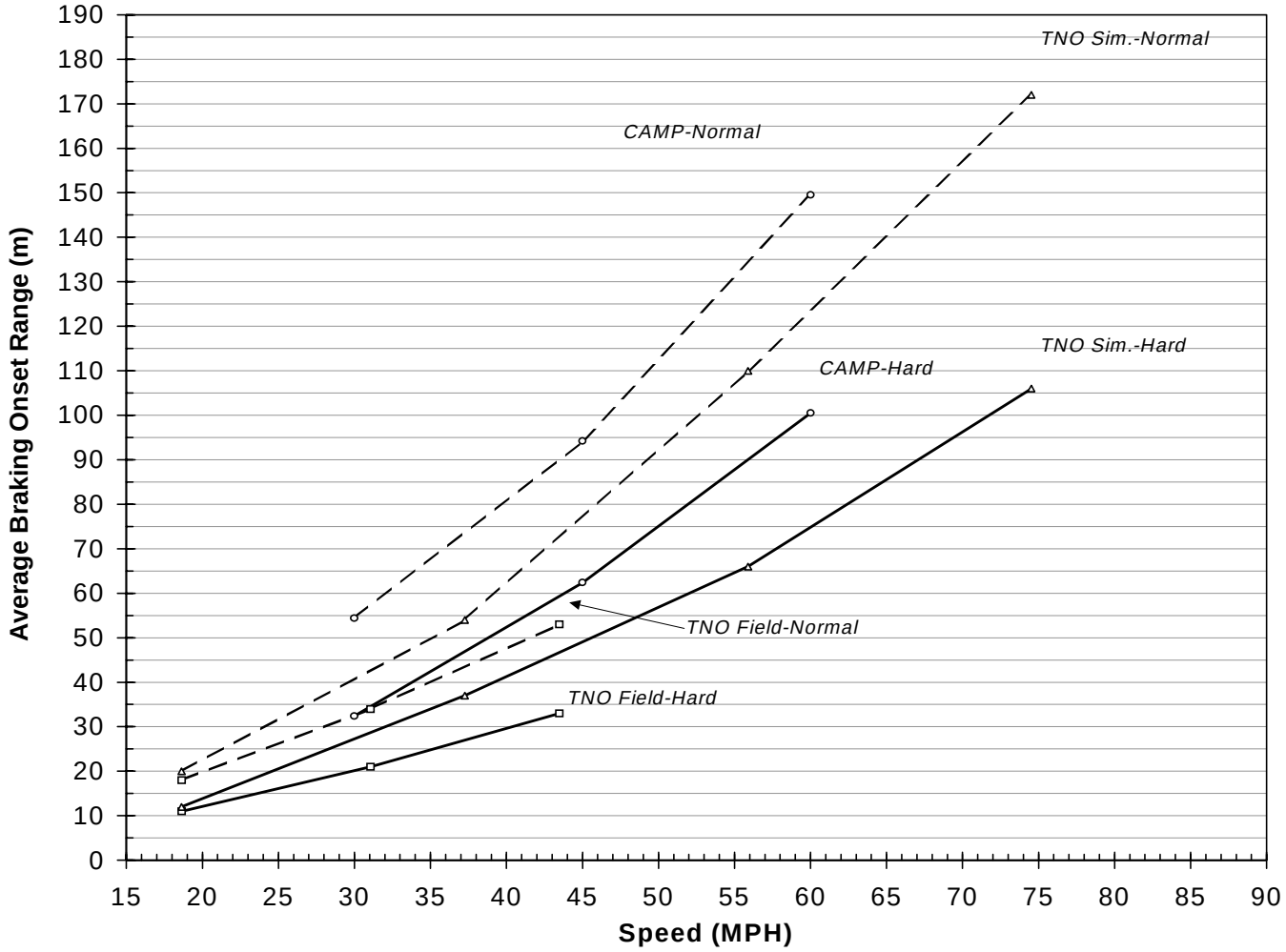

Figure 3-25 Range at Braking Onset for Normal and Hard Braking Instructions During Stationary Trials for the CAMP Study 1, Van der Horst (1990) TNO field study, and Kaptein et al. (1996) TNO Simulator Study

Comparison of Observed Data to Previous "Last-Second" Braking Judgment Data

Methodology of the CAMP Versus TNO Studies

It is worthwhile to compare the results of the current study to previously obtained results under closed-course conditions (van der Horst, 1990) and (fixed-base) driving simulator conditions (Kaptein et al., 1996). These two comparison studies were conducted by researchers at the TNO Institute for Human Factors in Soesterberg, The Netherlands.

In these studies, drivers were tested only under Stationary Trials conditions, and under nearly identical normal and hard braking instruction conditions relative to those used in the current CAMP study (the "comfortable hard" braking instruction was not employed). A few additional important differences between the current CAMP and previous TNO studies are worth stressing before comparing results across studies. First, unlike the current study where drivers were actively involved in controlling their speeds, driver's speeds in the TNO studies were controlled automatically via cruise control. Second, in the TNO closed-course study, drivers last-second braking judgments were made on an open airstrip (without any driving lane indications) while drivers approached a 2-dimensional Styrofoam mock-up of the rear-end of a vehicle mounted on a plastic barrel. Hence, relative to the current study, drivers' risk levels were substantially lower for with respect to hitting the target and avoiding the target by either a steering or combined steering/braking maneuver. With respect to the latter point, it should be noted that 1/10 mile markers mounted on metal poles were present on both sides of the test track, which are barely viewable in Figure 3-1 near the bridge underpass. Third, it is important to note that different speed conditions were used across the current CAMP and the two TNO studies, and hence, comparisons across these three studies are not entirely straightforward. Fourth, different age groups were used across the current CAMP and the two TNO studies. However, given the lack of and relatively small magnitude of age effects in the current study, these differences do not appear to be particularly problematic in making comparisons across studies.

Comparison of CAMP Versus TNO Studies Results

The average range at braking onset under normal and hard braking instructions for the current CAMP, and previous TNO closed-course and simulator studies are shown in Figure 3-25. These comparative results indicate that for both the normal and hard braking instruction conditions, average braking onset ranges are substantially longer (and hence, less aggressive/more conservative) in the current CAMP relative to both TNO studies. Under hard braking conditions, the average braking onset ranges in the current CAMP study are approximately 30%-75% longer across the 30-45 mph approach speeds relative to those observed in the TNO closed-course study (van der Horst, 1990). Similarly, the average braking onset ranges in the CAMP study are approximately 20%-35% longer across the 30-60 mph speeds relative to those observed in the TNO simulator study (Kaptein et al., 1996). It is interesting to note that the differences observed under hard braking conditions between the current CAMP and TNO studies increase with approach speeds, where driver's perceived risk levels may have been higher. In addition to these

results, it should be noted that consistent with the current CAMP study, the averaged required deceleration values in the TNO closed-course study increased with approach speeds (the TNO simulator study report does not report these values).

It should be stressed to the results found on the TNO simulator may be idiosyncratic to that particular simulator facility, and so that these results should not be automatically assumed to generalize to other driving simulators. One potential avenue of research, previously suggested by Kaptein et al. (1996) and supported by the current CAMP findings, would be to replicate the current study on a simulator study with motion-base capabilities.

It is interesting to note that based primarily on the two TNO studies discussed above conducted under Stationary Trial conditions, van der Horst and Hogema (1994) recommended as a potential crash alert timing approach to assume a constant 4-second TTC value. This value reflects an assumed (fixed) 1.5 second driver P-RT plus an assumed (fixed) 2.5 second TTC value at braking onset. With respect to this latter assumption, the current results suggest this crash alert timing approach would appear not be appropriate. As can be seen clearly in Figure 3-23, the assumption of a fixed TTC value (in the context of a fixed driver P-RT) appears dubious. Furthermore, even if one focuses on Stationary Trials (i.e., the condition actually tested by TNO), the assumed 2.5 second TTC value at SV braking onset appears to accommodate the *average* TTC-Case 2 values (e.g., rather than 85th percentile value) observed here only in the lowest approach speed condition tested (30 mph). (The reader should note that for Stationary Trials, the TTC-Case 2 measure is equivalent to TTC-Case 1 measure.)

"Real-World Validity" Implications of Differences Observed Across CAMP Versus TNO Studies

Overall, a "*target crash risk*" effects appears to be the most likely explanation for the observed differences across the current CAMP and TNO studies. That is, it appears that under lower target crash risk conditions (e.g., the TNO simulator and TNO closed-course study conditions described above), drivers are willing to begin hard braking later (i.e., at closer ranges to the lead vehicle) than under higher target crash risk conditions (e.g., the current CAMP study conditions). Most importantly, the observed differences suggest that attempts to define crash alert based on research which places drivers under minimal crash risk or no crash risk (e.g., simulator) conditions has the potential to lead to inappropriate and overly aggressive crash alert timing. An error in making the crash alert timing too aggressive in turn leads to the consequence of a decreasing the harm reduction potential of the FCW system. In addition, these results raise serious concerns about the real-world validity of previous FCW interface research which has employed substantially different crash alert timing approaches than suggested by these results (e.g., a fixed TTC criterion) and/or target crash risk conditions which may not be representative of those under which drivers would experience crash alerts (Graham et al., 1995; Hirst & Graham, in press; Janssen & Nilsson, 1990; Janssen & Thomas, 1994; McGehee, et al., 1996; Nilsson et al., 1991).

3.3.4 General Discussion

The primary goal of this initial CAMP study was to build a solid foundation for developing a crash alert timing and interface approach for a FCW system by exploring a number of performance measures. These measures were explored in the context of drivers performing "successful" (crash-free) last second braking maneuvers without a FCW system. In developing a crash alert timing approach for a FCW system, two fundamental parameters involving driver behavior have to be considered. One parameter is the time it takes for the driver to respond to the crash alert and begin braking (e.g., 1.5 seconds), and the second parameter is the driver deceleration (or braking) behavior in response to this alert across a wide variety of initial vehicle-to-vehicle kinematic conditions. This second parameter was the focus of the current study.

Converging evidence suggests that the 50th percentile required deceleration values observed in this study under the hard braking instruction condition appears very promising as an appropriate (not too early/not too late) estimate of the assumed driver braking onset range. The required deceleration level is defined here as the constant deceleration level required for the driver to avoid the crash at braking onset. More precisely, it is the constant deceleration level at braking onset required for the driver to avoid the crash assuming the current speeds of both the driver's vehicle and the lead vehicle, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing). Since the exact 50th percentile required deceleration values were effected by both speed and lead vehicle deceleration (i.e., the value changed across experimental conditions), modeling work was conducted aimed at predicting these values, which is described in detail in Appendix A20. This appendix also reports modeling efforts aimed at exploring the ability to predict these "last-second", "hard braking" onsets based on a subset of the available "ideal" data described above (e.g., assuming fixed driver and lead vehicle deceleration values).

It should stressed that the common assumption underlying previous crash alert timing approaches was to assume a fixed driver deceleration value independent of these kinematic variables. It is also important to note that the observed average required deceleration values were relatively independent of driver age or gender, which is a desirable characteristic from a FCW system production implementation perspective.

The required deceleration measure were tightly coupled with the actual deceleration measures, where the latter is simply a re-expression of driver's stopping distance given some initial speed. The lack of difference in results found between "comfortable hard" and "hard" braking instruction conditions suggest that drivers with a FCW-equipped vehicle would be capable of executing the observed "hard" braking levels without exceeding their "comfort zone" for hard braking. In addition, driver's were able to maintain the instructed speeds and appeared to follow at "normal" time headways prior to the last second braking judgment. This latter finding provides further evidence that these results found when the lead vehicle was moving may generalize to real-world driving.

In terms of allowing the driver sufficient collision warning distances to avoid a crash, the requirement for FCW sensing range generally increase as the difference in velocities (or delta V) between the following and lead vehicles increases. The 100 meters of sensor "knowledge"

accommodates potential crash alert warning distances for completing avoiding a crash for 90% of drivers in the second highest delta V condition tested, which involved the driver approaching the (stationary) parked lead vehicle target at 45 mph. Although the 100-meter criterion fell short in terms of avoiding any crash impact in the highest delta V condition tested (60-mph approach to the parked target). It should be noted that drivers could still experience substantial collision mitigation with a crash alert that is too late for avoiding any crash impact. It should be noted there are a number of caveats associated with this sensing range conclusion, including an assumed 1.7 second combined driver P-RT. Plus delay time, that the road surface coefficient of friction available can support the observed hard braking levels (dry roads were used here), and that drivers can at least match the hard braking levels observed in the current study under real-world conditions in response to a crash alert.

A comparing of these results to previous results obtained at the TNO Human Factors Research Institute (van der Horst, 1990; Kaptein et al., 1996) suggests that attempts to define crash alert timing based on research which places drivers under minimal or no (e.g., simulator) crash risk conditions the potential to lead to overly aggressive crash alert timing. This type of error could in turn lead to the consequence of decreasing the harm reduction potential of the FCW system. In addition, these results raise serious concerns about the real-world validity of previous FCW interface research which has employed substantially different crash alert timing than suggested by these results (e.g., a fixed 4-seconds time-to-collision criterion) and/or target crash risk conditions which may not represent those under which drivers would experience crash alerts (Graham et al., 1995; Hirst & Graham, in press; Janssen & Nilsson, 1990; Janssen & Thomas, 1994; McGehee, et al., 1996; Nilsson et al., 1991).

The results of this study were used in the three subsequent driver interface studies for crash alert timing purposes. More specifically, these results, and the subsequent modeling of these Study 1 results (see Appendix A20) aimed at predicting required deceleration values, formed the basis for assumptions regarding the assumed driver deceleration (or braking) behavior in response to the FCW crash alert in the subsequent driver interface studies. These interface studies focused on how to present a crash alert to the driver (i.e., visual, auditory, and/or haptic alerts), and provided an important opportunity to evaluate and validate these deceleration-based crash alert timing approach assumptions.

3.4 Abstract for Study 2, Study 3, and Study 4 - The Interface Studies

The goal of the human factors portion of the CAMP project was to define driver-interface requirements. More specifically, this effort is focused on defining when to present crash alerts (i.e., the crash alert timing) and how to present crash alerts to drivers (i.e., the crash alert modality). Developing a crash alert timing approach was the focus of Study 1, and the following three driver interface studies focused on how to present a crash alert to the driver (i.e., visual, auditory, and/or haptic alerts). These driver interface studies also provided an important opportunity to evaluate and validate the crash alert timing approach developed in Study 1. *The critical need for obtaining these data is dictated by the absence of data under controlled, realistic conditions involving drivers braking to a realistic crash threat while experiencing production-oriented crash alerts*.

In developing a crash alert timing approach for a Forward Collision Warning (or FCW) system, two fundamental parameters involving driver behavior need to be assumed. These parameters serve as input into straightforward vehicle kinematic equations that determine the alert range necessary to avoid a crash.

The first parameter is the time it takes for the driver to respond to the crash alert and begin braking (which included *driver brake reaction time*), and the second parameter is the driver deceleration (or braking) behavior in response to this alert across a wide variety of initial vehicle-to-vehicle kinematic conditions. Defining this second parameter of driver behavior was the focus of CAMP Study 1. In this study, a strategy was employed to initially develop a fundamental understanding of the timing and nature of drivers' "last-second" braking behavior *without* a FCW system, before conducting the subsequent FCW system driver interface studies. This strategy was taken so that drivers' perceptions of "normal" and "hard braking" kinematic situations could be properly identified and modeled for FCW system crash alert timing purposes. The underlying assumption of this experimental strategy is that properly characterizing (i.e., modeling) the kinematic conditions surrounding these hard braking onsets without FCW system crash alert support will lead to a proper estimate for the assumed driver deceleration (or braking) behavior in response to a FCW system crash alert across a wide variety of initial vehicle-to-vehicle kinematic conditions. This CAMP Study 1 is subsequently referred to as the "baseline" study.

The second fundamental crash alert timing parameter involving driver behavior which needs to be considered in developing a crash alert timing approach is driver brake reaction time (or *driver brake RT*). This second parameter was addressed in the three closed-course, field studies (all conducted at the GM Milford Proving Ground) reported here in the presence of various FCW system crash alert types under *unexpected (or surprise) braking event conditions*, which are discussed below.

The three driver interface studies reported here focused on how to present a crash alert to the driver (i.e., visual, auditory, and/or haptic alerts), and provided an opportunity to evaluate and validate the deceleration-based crash alert timing approach assumptions developed from the baseline study (i.e., the required deceleration parameter-based Study 1 predictive equation coupled

with a driver brake RT assumption). With respect to the latter point, results clearly indicated that the deceleration-based timing approach employed was subjectively rated by drivers (on average) as "just right" timing under a wide range of combinations of driver speed and lead vehicle decelerations under both expected and surprise braking event conditions. Most importantly, this crash alert timing approach allowed drivers to respond to the crash alert in a manner which allowed them to avoid impacts with the surrogate lead vehicle (or surrogate target).

Across these driver interface studies, younger, middle-aged and older drivers were tested. Drivers were asked to brake in response to various FCW system crash alert types while approaching the slowing or stopped surrogate target. Both alerted and unexpected (or surprise) braking event conditions were investigated with both trained and naive drivers. In two of the three studies, drivers were completely unaware the vehicle was even equipped with a FCW system crash alert prior to the unexpected, surprise braking event. Across these three driver interface studies during the surprise braking event conditions, several strategies were employed to ensure the driver experienced the crash alert and create a relatively "inattentive" driver (i.e., the criterion for triggering the crash alert was met). During the surprise braking event, the lead vehicle traveled at 30 MPH and braked at about -0.37 g's without brakelights activated. Strategies were employed to create a relatively "inattentive" driver including engaging the driver in natural conversation, asking the driver to respond to some background-type questions, and asking the driver to search the head-down, conventional instrument panel for a (non-existent) indicator light.

Across these driver interface studies, six separate crash alert types were evaluated in which the driver was simultaneously presented crash alerts from two sensory modalities (with one exception involving three modalities), sometimes referred to as a *1-stage, dual-modality crash alert*. The crash alert type conditions that were tested are indicated below:

- Head-Up + Non-Speech Tone
- High Head-Down Display + Non-Speech Tone
- High Head-Down Display + Speech message
- High Head-Down Display + Brake Pulse
- High Head-Down Display + Non-Speech Tone + Brake Pulse
- Flashing High Head-Down Display + Non-Speech Tone (for the other crash alert types, the High Head-Down Display was not flashed and remained steady)

The visual alert components evaluated included a "high" head-down display (or HHDD) and a head-up display (or HUD). The visual format of these displays (a "car-star-car" crash icon with the word "WARNING" printed below) was selected from a set of alternatives by using an established ANSI procedure for evaluating candidate symbols. The auditory alert components evaluated included a non-speech sound and a speech sound (the word "warning" repeated), which were played through the front car speakers. These two sounds were selected based on a laboratory study involving drivers rating various alternative sounds on crash alert properties. The haptic alert evaluated was a brief brake pulse, or "vehicle jerk" alert. This alert was examined with more

intent to explore its potential, since unlike the visual and auditory alerts examined here, there are important unresolved implementation issues surrounding this alert.

The key dependent measures were drivers' brake RTs (particularly during surprise braking event conditions), drivers' required and actual (or observed) decelerations in response to the crash alerts, the extent to which drivers noticed the various crash alerts under surprise braking event conditions, and drivers' subjective ratings of both the crash alert timing and FCW system crash alert types examined.

Results indicated differences in both objective (performance) data and subjective (questionnaire-oriented) data across the crash alert types examined. The key findings were as follows. First, the crash alert type conditions including a non-speech tone component resulted in faster brake RTs relative to the crash alert type including a speech component. Second, drivers rated the crash alert types including either a speech or brake pulse component as more annoying relative to the remaining crash alert types, under the assumption that FCW system crash alerts would occur in non-threatening situations between once a day to once a week. Third, the brake pulse alert provided a "vehicle slowing" advantage during the delay time interval between when the crash alert timing was violated and when the driver braked, such that the driver was in a more conservative kinematic scenario at braking onset relative to the crash alert types examined not including this alert component. Furthermore, adding a non-speech tone component to the brake pulse alert significantly reduced the relatively slow brake RTs initially observed in the HHDD + Brake Pulse condition. Fourth, although there were no performance differences associated with the relevant HHDD versus HUD comparisons, subjects indicated a strong preference for the HUD. In a related finding, for a 1-stage crash alert approach, drivers indicated a strong preference for a multi-modality crash alert approach (particularly a dual-modality crash alert approach). Fifth, after the surprise braking event was experienced by naive drivers, nearly all drivers reported noticing non-speech tone, speech, and brake pulse components of these crash alert types examined, and significantly more drivers noticed the Flashing HHDD and steady HUD relative to the steady HHDD.

In addition to these crash alert modality (or crash alert type) differences, brake RTs observed under the surprise technique which resulted in the highest upper percentile values (the head-down visual search task) yielded 85th to 95th percentile (i.e., slower) RTs of 1.2 and 1.5 seconds, respectively.

Of the 1-stage, FCW crash alert types examined, the "Flashing HHDD + Non-Speech Tone" is recommended as a near-term approach (Replacing the flashing HHDD with a "steady" HUD" is also supported by these findings.). The "Steady HHDD + Non-Speech Tone" crash alert type provided good all-around performance in terms of both objective data (e.g., fast driver brake RTs) and subjective data (e.g., low driver annoyance). The recommendation to flash the HHDD is primarily based on improving the noticeability of the HHDD for drivers who may not hear the non-speech tone either due to hearing impairments and/or noises coming from either inside or outside the vehicle. Other considerations include potentially facilitating the driver to look ahead in response to the visual crash alert, and using this visual alert to help explain the non-speech tone to the driver. The recommended visual display format is (a "car-star-car" crash icon with the word "WARNING" printed below) and non-speech tone correspond to those tested in these three

interface studies. Although a multiple-stage alert is allowed under the proposed requirement, a 1-Stage alert is recommended based on the current discovery of a proper "single-point" crash alert timing approach, compatibility with Adaptive Cruise Control system driver alerts being considered, simplicity/elegance from a customer education (mental model) and production implementation perspective, minimizing nuisance alerts (which can reduce system effectiveness, and the rapid (potentially confusing) sequencing of multi-stage alerts in many closing scenarios likely to trigger crash alerts.

A critical consideration in recommending the "Flashing HHDD + Non-Speech Tone" alert as a near-term FCW crash alert approach is that this alert type has favorable qualities from an industry-wide, international implementation perspective relative to the HUD, brake pulse, and speech crash alert components examined. (In any case, the speech alert component performed poorly in terms of both objective and subjective data.). In the near-term, HUDs will not be implemented industry-wide. Furthermore, as discussed above, there are important unresolved implementation and driver behavior issues surrounding the brake pulse alert (and haptic alerts in general).

Based primarily on data from these three interface studies and the previous baseline study (CAMP Study 1), a set of minimum driver interface requirements were developed, which are discussed in Chapter 4.

3.5 Introduction for Interface Studies

Purpose of CAMP Human Factors Studies 2, 3, and 4

This research describes three closed-course, field studies aimed at exploring human factors issues surrounding forward collision warning systems (i.e., the effects of this collision warning system and associated interfaces on driver behavior). More specifically, this research explored human factors issues surrounding *Forward Collision Warning* (or *FCW*) systems which have not been adequately addressed by the relatively limited number of previous human factors studies conducted either under laboratory conditions (Graham, Hirst, & Carter, 1995; Hirst & Graham, in press) or driving simulator conditions (Janssen & Nilsson, 1990; Janssen & Thomas, 1994; McGehee, Dingus, & Wilson, 1996; Nilsson, Alm, & Janssen, 1991).

Overall, this CAMP human factors effort is focused on defining <u>when</u> to present crash alerts (i.e., the crash alert timing) and <u>how</u> to present crash alerts to drivers (i.e., the crash alert modality) by exploring a number of objective and subjective driver measures. *The critical need for obtaining these data is dictated by the absence of data under controlled, realistic conditions involving drivers braking to a realistic crash threat while experiencing production-oriented crash alerts.* In CAMP Study 1, a strategy was employed to initially develop a fundamental understanding of the timing and nature of drivers' "last-second" braking behavior *without* a FCW system, before conducting the subsequent FCW system driver interface studies. This strategy was taken so that drivers' perceptions of "normal" and "hard braking" kinematic situations could be properly identified and modeled for FCW system crash alert timing purposes. The underlying assumption of this experimental strategy is that properly characterizing (i.e., modeling) the kinematic conditions surrounding these hard braking onsets without FCW system crash alert support will

lead to a proper estimate for the assumed driver deceleration (or braking) behavior in response to a FCW system crash alert across a wide variety of initial vehicle-to-vehicle kinematic conditions.

As was noted above, previous research examining FCW system interfaces (and timing) have been conducted under either laboratory or driving simulator conditions, and these results have not been validated under real-world driving conditions. A comparison of CAMP Study 1 results to previous driving simulator research suggested that attempts to define crash alert timing under conditions which place drivers under minimal or no crash risk conditions (e.g., driving simulator conditions) has potential to lead to overly aggressive crash alert timing. This type of error could in turn lead to the consequence of decreasing the harm reduction potential of the FCW system. In addition, this comparison raises serious concerns about the real-world validity of previous FCW system interface research which has employed substantially different crash alert timing than that suggested by the CAMP Study 1 results (e.g., a fixed 4-seconds time-to-collision criterion) and/or target crash risk conditions which may not represent those under which drivers would experience crash alerts.

In developing a crash alert timing approach for a FCW system, two fundamental parameters involving driver behavior need to be assumed. These parameters serve as input into straightforward vehicle kinematic equations that determine the alert range necessary to avoid a crash. The first parameter is the time it takes for the driver to respond to the crash alert and begin braking (which includes *driver brake reaction time*), and the second parameter is the driver deceleration (or braking) behavior in response to this alert across a wide variety of initial vehicle-to-vehicle kinematic conditions. Defining this second parameter of driver behavior was the focus of the CAMP Study 1, during which drivers performed “last second” braking without the benefit of FCW system support. This study is subsequently referred to as the “baseline” study. The second fundamental crash alert timing parameter involving driver behavior, which needs to be considered in developing a crash alert timing approach is: driver brake reaction time (or *driver brake RT*). This second parameter was addressed in the three closed-course, field studies (all conducted at the GM Milford Proving Ground) reported here in the presence of various FCW system crash alerts under *surprise braking event conditions*, which are discussed below.

The three driver interface studies reported here focused on how to present a crash alert to the driver (i.e., visual, auditory, and/or haptic alerts), and provided an opportunity to evaluate and validate the crash alert timing approach assumptions developed from the baseline study (i.e., the required deceleration parameter-based Study 1 predictive equation coupled with a driver brake RT assumption).

3.6 Overview of Methodological Approach for Interface Studies

Overall, the goal of the current studies is to gather data of the highest real-world validity possible under controlled closed-course conditions. An overview of the experimental methodology and approach used in the three studies described below is shown in Table 3-11, and an overview of the order of experiment events (or procedures) in these three studies is shown in Table 3-12. For each of these studies, data was gathered on the same 1-mile straightaway and under the same general vehicle-to-vehicle spacing conditions which were used for CAMP Study 1.

Across these driver interface studies, younger, middle-aged and older drivers were tested under closed-course field conditions. Drivers were asked to respond to various FCW system crash alerts while approaching the slowing or stopped surrogate target. Both alerted and unexpected (or surprise) braking event conditions were investigated with both trained and naive drivers. In two of the three studies, drivers were completely unaware the vehicle was even equipped with a FCW system crash alert prior to the unexpected, surprise braking event. Several strategies were employed to ensure the driver experienced the crash alert (i.e., the criterion for triggering the alert was met) during the surprise braking event conditions and to create a relatively "inattentive" driver. Strategies used to create an inattentive driver included engaging the driver in natural conversation (used in Study 2), asking the driver to respond to some background-type questions (used in Study 3), and asking the driver to search the head-down, conventional instrument panel for a (non-existent) indicator light (used in Study 4).

During this unexpected, surprise braking event, the lead vehicle traveled at 30 mph and braked at 0.36-0.38 g's without brake lights activated (average lead vehicle deceleration values caused by the "automatic" brake controller varied slightly across studies). The rationale for choosing this lead vehicle speed and deceleration conditions were two-fold. First, for safety reasons, it was felt the surprise event should be run initially at the lowest speed condition tested (i.e., 30 mph). Second, 6 surrogate target impacts occurred in CAMP Study 1, which can be thought of as a failure to execute appropriate braking by both the driver and experimenter (the latter who had access to add-on brakes). Of the 12 distinct lead vehicle speed/lead vehicle deceleration combinations investigated in CAMP Study 1, 4 of the 6 impacts occurred in the 30 mph /-0.39 g combination condition. Hence, it appears this scenario may be particularly problematic for making appropriate "last-second" hard braking judgments. These surprise braking event conditions (i.e., the POV speed and POV deceleration profile) were held constant across each of the three studies reported, and are subsequently referred to collectively as the *Surprise Moving Trial*. Drivers were also asked to repeat the surprise braking event condition as an alerted driver for comparison purposes.

Table 3-11 Overview of Study 2, Study 3, and Study 4 Methodology

Method Issue	Study 2	Study 3	Study 4
Subjects from CAMP Study 1?	Yes	No	Yes
Number of younger/middle/ older aged subjects tested (Gender split)	8 / 8 / 8 (n=24)	0 / 30 / 30 (n=60)	8 / 8 / 8 (n=24)
Study Phases	(1ST) Alerted Stationary (2ND) Surprise Moving (3RD) Follow-on Moving	(1ST) Surprise Moving (2ND) Follow-on Moving	(1ST) Surprise Moving (2ND) Alerted Moving
Instructions During Alerted Trials	Maintain steady speed (during Stationary Trials) or follow normally (during Moving Trials). Brake immediately in response to crash alert in order to avoid crash.		
Alerted Trials Scenarios	Approach parked car at 30 or 60 mph. Crash alert timings used: "RDP", "RDP + 0.05 g", "RDP + 0.10 g". Driver RT = 0.52 sec.	Not applicable.	Approach moving car traveling at 30, 45, or 60 mph. Lead car brakes at either -0.15, -0.27, or -0.36-0.38 g's. "RDP" timing used. Driver RT = 0.52 sec.
Surprise Moving Trial Technique	Natural Conversation	Background Q & A	Head-Down Telltale Search
Surprise / Follow-On Trials Scenario	Lead vehicle travels at 30 mph and brakes at -0.36 to -0.38 g's without brakelights. "RDP" crash alert timing used. Driver RT assumption = 1.5 seconds for Surprise trial.		
Crash Alert Types Tested (1-stage, primarily dual-modality)	HUD + Non-Speech HHDD + Non-Speech HHDD + Speech HHDD + Pulse	→ → → HHDD + Pulse + Non-Speech Flashing HHDD + Non-Speech	→ →
"Key" Dependent Measures	Brake RT, Required deceleration, Actual deceleration, Crash alert timing and Interface appropriateness ratings, and Visual telltale noticeability		

Table 3-12 Procedure Orders for Study 2, Study 3 and Study 4

Performance Data	Brief Procedure Description	Study		
		2	3	4
Alerted Stationary Trials	4 blocks of 6 trials; a different crash alert type used for each block. Alerted driver approaches parked surrogate target at either 30 or 60 mph, and brakes to alert.	1		
Surprise Moving Trial	One trial; POV speed 30 mph, POV deceleration –0.36 to –0.39g, no POV brakelights. Unexpected (or surprise) braking event triggers alert. Various driver distraction techniques employed.	2	1	1
Alerted Moving Trials	18 trials varying speed, POV deceleration, and crash alert timing. Alerted driver follows moving surrogate target, and brakes to alert when target slows.			2
Follow-on Moving Trials	Trials following surprise trial. Conditions identical to Surprise Moving Trial except driver is alerted to braking event.	3	2	
Subjective Data				
Alert Noticeability Questionnaire	Naive participant reported alerts noticed during post-Surprise Moving Trial interview.		1[a]	1[a]
Timing Rating	Participant rated crash alert timing on a scale ranging from 1 (much too early) to 7 (much too late).	1[a], 2[a], 3[a]	1[a],2[a]	1[a],2[a]
Alert Modality Appropriateness Questionnaire	Participant rated modality-specific characteristics of alert (e.g., brightness, duration, intensity).	1[b]	2[b]	
Crash Alert Appropriateness Questionnaire	Participant rated warning characteristics of multi-modality crash alert types experienced (e.g., confusability, annoyance, startle).	4	3	
Build an Interface Questionnaire	Participant selected preferred alert(s) under 1-stage alert assumptions, and then under 2-stage alert assumptions.	5		
Name the System Questionnaire (open-ended)	Participant generated possible name for alert system.	6		
Name the System Questionnaire (forced choice)	Participant chose three preferred names for alert system from a list of names.	7	4	

[a]Refers to subjective data gathered on corresponding “performance data” trial.
[b]The Alert Modality Appropriateness Questionnaire was completed for each alert type after each block of trials.

Across these driver interface studies, six separate crash alerts were evaluated in which the driver was simultaneously presented crash alerts from two sensory modalities (with one exception involving three modalities), sometimes referred to as a 1-stage, dual-modality crash alert. The visuals alert components evaluated included a “high” head-down display and a head-up display (or HUD). The visual format of these displays (a “car-star-car” crash icon with the word “WARNING” printed below) was selected from a set of alternatives by using an established ANSI procedure for evaluating candidate symbols. The auditory alert components evaluated included a non-speech sound and a speech sound (the word “warning” repeated), which were played through the front car speakers. These two sounds were selected based on a laboratory study involving drivers rating various alternative sounds on crash alert properties. The haptic alert evaluated was a brief brake pulse, or “vehicle jerk” alert. This alert was examined with more of an intention to explore its potential, since unlike the visual and auditory alerts, there are important unresolved implementation and driver behavior issues surrounding this alert.

The rationale for evaluating 1-stage rather than multiple-stage (e.g., a 2-stage cautionary alert/imminent alert approach) crash alert types was based in part on results from CAMP Study 1. The 50th percentile required deceleration value observed in that study under “hard braking” driver instructions appeared very promising as an appropriate (not too early/not too late) single point estimate of the assumed driver braking onset range (or distance) for crash alert timing purposes. The required deceleration measure was defined, as the constant deceleration level required for the driver to avoid the crash at braking onset. This measure was calculated by using the current speeds of the driver’s vehicle and the lead vehicle, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current “constant” rate of slowing). Put in another way, it was felt that this required deceleration-based estimate would ensure that, for a high percentage of drivers, the onset of braking in response to a crash alert would:

1. Occur at a closer range than their braking onset range during “aggressive” normal braking.

2. Allow sufficient range for the driver to avoid the crash.

The required deceleration data from CAMP Study 1 was modeled (explained further below) and provided the basis for assumptions made about driver braking onset range. It is important to note that these required deceleration values were relatively uninfluenced by driver age or gender in CAMP Study 1, which is a desirable finding from a production implementation perspective. Furthermore, it was felt that the low percentage of drivers not accommodated by (2) above (allowing sufficient range for the driver to avoid the crash) would brake harder in response to a crash alert (i.e., they were *capable* of braking harder) than what was observed during their preferred “last second” hard braking in CAMP Study 1.

Additional reasons for employing a 1-stage rather than multiple-stage crash alert approach were the following. First, with respect to the compatibility of a FCW system integrated with an Adaptive Cruise Control (or ACC) system, a 1-stage alert is more consistent with the 1-stage ACC system driver alerts being considered (e.g., one possible ACC alert is to warn the driver if they have exceeded the maximum braking deceleration authority of the ACC system). Early production implementations of FCW systems are likely to be integrated with ACC. Since an ACC

system alert may be largely consistent with the meaning intended by a FCW system alert (i.e., a collision may occur unless evasive control action is taken), the use of a 1-stage alert for both ACC and FCW systems may be promising from a customer education, simple "mental model" perspective.

Second, with respect to a "stand-alone" FCW system, a 1-stage alert is much more simple and elegant from a customer education ("mental model") and production implementation perspective. For example, the driver only has to interpret the meaning of one (versus more than one) alert. In addition, if the alert timing (or criterion) is under driver control, the effect of the driver adjusting a 1-stage alert criterion is relatively straightforward. In a multiple-stage alert scheme, the effect of such an adjustment is less straightforward. For example, do adjustments effect multiple alert stages? Are adjustments permitted for the most imminent alert?

Third, a 1-stage alert provides a potential means of reducing in-path ("too early") nuisance alerts and out-of-path nuisance alerts relative to the first stage of a 2-stage (or multiple-stage) crash alert approach. In this case, it is assumed the first stage of a 2-stage (or multiple-stage) alert approach would be more conservative (i.e., the alert would occur earlier or at a farther range to the vehicle ahead) than a 1-stage alert. These increases in nuisance alerts could reduce system effectiveness (e.g., drivers' brake RTs to the alert could increase), system usage in FCW-equipped vehicles (i.e., drivers may turn the system off), and negatively impact driver acceptance of FCW systems. On the other hand, it could be argued that, providing these "first stage" nuisance alert concerns could be addressed, a properly designed 2-stage approach might give the driver an earlier opportunity to avoid "near misses" and situations where evasive control action must be taken immediately, as well as respond earlier under poor traction or poor atmospheric conditions. However, these potential benefits of a 2-stage crash alert approach may also be able to be attained with a 1-stage crash alert with an adjustable crash alert timing feature.

Fourth, based on CAMP experiences during pilot testing attempting to sequence the 1-stage alert and the "bail-out" alert (i.e., the alert was used to signal the passenger-experimenter to take over and begin braking), which can be thought of as but one example of a 2-stage alert, a concern was identified that the extremely short time lag between the two crash alerts might render the 2-stage alert distinction meaningless and potentially confusing for the driver. Hence, this raises the possibility that under the wide range of vehicle-to-vehicle kinematic scenarios likely to trigger crash alerts examined in these CAMP studies, a 2-stage alert may be more confusing than helpful for the driver. More generally, rapid sequencing of multi-stage alerts are more likely to occur under conditions when the driver's vehicle is rapidly closing in on the lead vehicle such that the difference in speeds between these two vehicles (i.e., the delta velocity) is building up rapidly. (Conversely, slower sequencing of multi-stage alerts are less likely to occur under conditions when the driver's vehicle is slowly closing in on the lead vehicle such that the difference in speeds between these two vehicles (i.e., the delta velocity) is building up slowly.) Examples of conditions under which rapid sequencing may occur include when the driver of an FCW-equipped vehicle is approaching a stopped or braking lead vehicle, as well as under various cut-in/merge and lane change situations. It should be stressed that the distinction between the moments at which "soon" and "immediate" evasive control action are required, associated with cautionary and imminent crash alerts, respectively, is solely dependent on a particular crash alert timing approach. If this distinction is relatively minor under most vehicle-to-vehicle kinematic

conditions (causing a rapid, potentially confusing sequencing of these alerts), particularly if those conditions are relatively more serious in nature, then the merits of a 2-stage alert are questionable. It is worth noting that the previous recommendation made by Lerner, Kotwal, Lyons, and Gardner-Bonneau (1996) for 2-stage automotive crash alerts was based on research examining aircraft alerting systems, which may have very different alert timecourses (e.g., slower-developing timecourses) relative to automotive crash alert systems.

Indeed, one could argue that multiple-stage (e.g., 2-stage) alerts should be avoided unless the advantages of using such alerts outweigh the disadvantages of such alerts. As discussed above, potential disadvantages of multiple-stage alerts relative to a 1-stage alert include potential non-compatibility with ACC system driver alerts, increases in system complexity from a customer education (driver mental model) perspective, increases in system complexity from a production implementation perspective (e.g., added controls and displays), and increases in nuisance alerts which could reduce system effectiveness.

The rationale for evaluating dual-modality warnings in these studies was based on the notion that an omnidirectional component of the crash alert (i.e., an auditory or haptic component) was required which was independent of where the driver was directing visual attention, and that adding a (non-omnidirectional) visual crash alert was a prudent strategy for a crash alert modality approach. With respect to the former point, an omnidirectional alert component is required since an inattentive or distracted driver (who play large roles in rear-end collisions) may not detect a visual crash alert display, since their visual attention may be directed elsewhere (e.g., at an instrument panel display) at the same time the alert is initially presented. With respect to this latter point, a visual crash alert is recommended in order to accommodate drivers who may not hear the alert sound either due to hearing impairments (e.g., older, hearing-impaired drivers or deaf drivers) and/or competing noises coming from either inside or outside the vehicle. One advantage of visual over auditory displays is that whereas driver licensing requirements in most states in the United States generally do require a minimum level of visual performance (e.g., 20/40 far acuity, adequate peripheral vision), they generally do not require any minimum level of auditory performance. Additional important reasons for including a visual alert modality component are to potentially facilitate the driver to look ahead in response to the crash alert if they are not currently looking ahead at the forward scene, and to help explain the omnidirectional component of the alert to the driver. With respect to this latter point, it is currently common industry practice to provide a visual indicator for most telltale-related sounds. For these reasons, a visual alert (either a “high” head-down display or head-up display) was always included as a component in each of the multi-modality (either dual-modality or tri-modality) crash alert types investigated.

Various objective measures were analyzed. The key dependent measures were drivers’ brake RTs (particularly during the Surprise Moving Trial). Drivers’ required and actual (or observed) decelerations in response to the crash alerts, the extent to which drivers noticed the various crash alerts under the Surprise Moving Trial conditions, and drivers’ subjective ratings of both the crash alert timing and FCW system crash alert types examined. The variable definitions, and the point in time during the braking maneuver in which the performance measures were analyzed (at POV braking onset, at SV braking onset, throughout the braking, end of the braking maneuver) are identical to that used in Study 1, with the exception of one new measure, driver’s brake reaction

time (RT). This measure is defined as the time between crash alert onset and the driver contacting the brake (i.e., triggering the brake switch) in response to the alert. (Also, it should be noted that unlike CAMP Study 1, SV braking onset was defined relative to the brake switch trigger point, since drivers braked in a “crisp”, firm manner in response to the alert (rather than sometimes hovering over the brake as was observed during “last-second” braking judgments in CAMP Study 1).