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Forward Collision Warning Requirements Project Final Report - Task 1

Refining the CAMP Crash Alert Timing Approach by Examining "Last Second" Braking and Lane-Change Maneuvers Under Various Kinematic Conditions

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16. Abstract

This final report describes a follow-on study to the previous Crash Avoidance Metrics Partnership (CAMP) human factors work addressing Forward Collision Warning (FCW) timing requirements. This research extends this work by gathering not only "last-second" braking maneuver data, but also data from "last-second" steering (or lane-change) maneuvers. Drivers performed last-second braking and steering maneuvers under instructions for "normal" or "hard" intensity responses under a wide variety of vehicle-to-vehicle kinematic scenarios. This strategy of varying instruction during these last-second maneuvers was taken so that drivers' perceptions of "normal" and "non-normal" kinematics situations (or envelopes) could be properly identified and modeled for crash alert timing purposes. In addition, unlike the previous CAMP work that only examined lead vehicle stationary and lead vehicle braking scenarios, the current study also included scenarios where the lead vehicle was moving at a slower but constant speed prior to the last-second maneuver. Results provided validation of the Required Deceleration Model developed in the prior CAMP FCW project. In addition, a new model was developed, referred to as the "3-Tiered Inverse Time-To-Collision Model". This promising model assumes the driver deceleration response (in response to the crash alert) is based on an inverse Time-To-Collision (TTC) threshold that decreases linearly with speed. One advantage of this model is that it requires only coarse (rather than accurate) knowledge of lead vehicle deceleration levels.

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Executive Summary

The current project builds upon the foundation provided by the human factors work conducted in the previous Crash Avoidance Metrics Partnership (CAMP) / NHTSA Forward Collision Warning system program. This project involves two major lines of research. The first line of research is aimed at understanding the relationship between data obtained employing the CAMP "surrogate target" methodology (described below) under closed-course conditions and data obtained with the recently constructed National Advanced Driving Simulator (NADS). A second line of research is aimed at evaluating and potentially refining the preliminary crash alert timing approach developed in the previous CAMP Forward Collision Warning (FCW) project under a wider range of conditions. This issue is addressed by employing the surrogate target (closed-course) methodology developed in this previous program, which is illustrated on the cover of this report. This methodology allows experimenters to safely place naive drivers in realistic rear-end crash scenarios on a closed test track and observe their behavior. The surrogate target consists of a molded composite mock-up of the rear half of a passenger car mounted on an impact-absorbing trailer which is towed via a collapsible beam. The surrogate target is able to absorb impacts of up to 10 miles per hour velocity differential without sustaining permanent damage.

This interim report describes the first study in a series of four planned follow-on studies to this earlier CAMP FCW work. The current study is the first of two studies conducted under the second line of research described above. In developing a FCW crash alert timing approach, two fundamental driver behavior parameters should be considered. These parameters serve as input into vehicle-to-vehicle kinematic equations which determine, given a set of assumptions, the alert range necessary to assist the driver to avoid a potential crash. The first driver behavior parameter is the time duration required for the driver to respond to the crash alert and begin braking, referred to as driver brake reaction time. (This brake reaction time assumption is added to other system delay times, such as interface delay times and brake system delay times.) This parameter was developed in the previous CAMP FCW work under conditions in which drivers experienced an unexpected rear-end crash scenario. The second driver behavior parameter needed for a crash alert timing approach is the driver deceleration (or braking) behavior in response to the FCW alert under a wide range of vehicle-to-vehicle kinematic conditions and scenarios. This parameter was developed in the previous CAMP FCW work under conditions in which alerted drivers made last-second braking maneuvers. This second parameter was the focus of the current study.

Unlike the previous CAMP FCW human factors work, the current study examined not only "last-second" braking, but also "last-second" steering (or lane-change) maneuvers. Drivers performed last-second braking maneuvers using two different braking instructions. The first instruction asked drivers to maintain their speed and brake at the last second possible in order to avoid colliding with the target using "normal" braking intensity or pressure. The second instruction asked drivers to maintain their speed and brake at the last second possible to avoid colliding with the target using "hard" braking intensity or pressure. Similarly, drivers performed last-second steering maneuvers using two different steering instructions. The first instruction asked drivers to maintain their speed and change lanes at the last second they "normally would to go around the target". The second instruction asked drivers to maintain their speed and change lanes at the last second they "possibly could to avoid colliding with the target". This strategy of varying instruction during these last-second maneuvers was taken so that drivers' perceptions of "normal" and "non-normal" kinematic situations (or envelopes) could be properly identified and modeled for crash alert timing purposes. In addition, unlike the previous CAMP work which only examined lead vehicle stationary and lead vehicle braking scenarios, the current study also included kinematic scenarios where the lead vehicle was moving at a slower but constant speed prior to the last-second maneuver. Finally, it should be noted that the current data set was gathered at the Transportation Research Center in East Liberty, Ohio, whereas previous work was conducted at the GM Proving Ground in Milford, Michigan.

There were two key findings that emerged from the observed last-second maneuver (braking and steering) onset behavior. First, the differences observed in last-second braking behavior as a function of test site (Milford Proving Ground versus Transportation Research Center), age (20-30, 40-50, and 60-70 year olds), and gender (male, female) were relatively small in magnitude. Second, differences were observed between last-second braking onsets and last-second steering onsets, and these differences clearly indicate that the relative timing of last-second braking onsets versus last-second steering onsets is highly dependent on the kinematic conditions. Under nearly all 60 MPH conditions examined, mean steering onsets when drivers were instructed to change lanes at the last second possible tended to occur later (i.e., were more aggressive) than mean braking onsets when drivers were instructed to brake at the last second possible using hard braking pressure. (This difference was not observed under the 30 MPH speed conditions examined.) Furthermore, the magnitude of this effect increased as the difference in speed between the lead and following vehicles (or delta velocity) increased. The consequence of this effect (i.e., last-second steering onsets occurring later than last-second braking onsets) on potential nuisance alerts during intentional lane changes will be discussed shortly in the context of braking onset model predictions.

These observed last-second maneuver data were modeled for predicting hard braking onset (or driver deceleration behavior), which as indicated above, is one of two driver behavior parameters needed for a crash alert timing approach. The database modeled includes 3,536 last-second braking judgment trials and 790 last-second steering (or lane-change) judgment trials. Two braking onset models were developed using this database. The first model was developed using linear regression techniques and the second model was developed using logistic regression techniques.

The first model developed for predicting hard braking onset is nearly identical to the Required Deceleration Model developed in the first CAMP FCW project. This lack of change in the Required Deceleration Model provides validation for the previous model, and indicates that this model is robust and relatively unaffected by the new vehicle-to-vehicle kinematic conditions that were included in this expanded data set. This model predicts a required deceleration value at brake onset above which the driver is assumed to be in a last-second, hard braking onset (alert appropriate) condition. This model uses as inputs closing speed between the following and lead vehicle, the lead vehicle deceleration value, and knowledge of whether or not the lead vehicle is moving or stationary.

The second braking onset model developed is referred to as the “3-Tiered Inverse Time-to-Collision” Model. This model predicts the probability that a driver is in a last-second, “hard” braking onset situation (and hence, not in a last-second, “normal” braking onset situation). This model includes inverse time-to-collision (i.e., the difference in speeds between the following and lead vehicles divided by the range between these two vehicles) as a key component. The three tiers of the model refer to the three separate equations which were developed for lead vehicle stationary, lead vehicle moving and braking, and lead vehicle moving and not braking cases. Note that this model, unlike the Required Deceleration Model needs only coarse (rather than accurate) knowledge of lead vehicle deceleration. This is a potential advantage of this model since sensing lead vehicle deceleration in an accurate, real-time fashion is technologically challenging. This 3-Tiered Inverse TTC model can be elegantly described as a model that assumes the driver deceleration response (in response to the crash alert) is based on an inverse TTC threshold that decreases linearly with speed.

These two models were compared on several criteria, including predictions under "nominal" vehicle-to-vehicle kinematic conditions observed in the database, differences between predicted and observed braking onset values, estimates of the number of predicted hard braking onsets which were considered as either "early" or "late" (based on certain assumptions), and predicted performance under conditions beyond the scope of the current database. Results showed that the new 3-Tiered Inverse TTC Model provided very comparable (and in some cases, more favorable) performance relative to the slightly revised Required Deceleration Model. A domain of validity check performed with a large range of vehicle-to-vehicle kinematic conditions beyond the current database also showed both models behaved very comparably and "sensibly" (e.g., predicted required deceleration values at braking onset were less than 0.45 g's, with the exception of some extreme kinematic conditions).

This newly developed 3-Tiered Inverse Time-to-Collision Model offers the advantage of the greater flexibility afforded by operating in the "probability of hard braking onset" domain, since the "probability of hard braking" value inherent to this model can be altered in a straightforward manner with relatively clear supporting underlying rationale. This value could be potentially altered to address driver characteristics, weather and environmental conditions, and potential nuisance alerts during normal, intentional lane-change maneuvers. Finally, although the Required Deceleration Model may perform comparably from a predictive sense, additional considerations suggest the 3-Tiered Inverse Time-to-Collision Model may better represent the underlying mental process drivers use in deciding when to brake hard.

Further analyses were conducted to investigate the extent to which an alert might be issued prior to an intended "normal" lane-change maneuver, based on brake onset predictions from these two models. For these models, overall estimates of the incidence of "normal", last-second lane change onsets in the current database occurring closer to the lead vehicle than the predicted (alert-appropriate) braking onsets were slightly higher than 15%. These results suggest that an alert timing approach based only on last-second braking considerations (i.e., an approach which does not consider last-second steering considerations) may result in alerts occurring before the point at which some drivers execute "normal" (albeit last-second) lane change maneuvers.

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

Introduction

The current project builds upon the foundation provided by the human factors work conducted in the previous Crash Avoidance Metrics Partnership (CAMP) / NHTSA Forward Collision Warning system program (Kiefer, LeBlanc, Palmer, Salinger, Deering, and Shulman, 1999). This interim report describes the first study in a series of four planned studies. These four studies involve two major lines of research.

The first line of research is aimed at understanding the relationship between data obtained employing the CAMP "surrogate target" methodology (described below) under closed-course conditions and data obtained with the recently constructed National Advanced Driving Simulator (NADS). Two studies will be conducted under this line of research. One study of this simulator-based effort is aimed at comparing "last-second" braking and "last-second" steering maneuvers under closed-course versus simulator conditions. The closed-course data used in this comparison will be obtained prior to the simulator data (as described below in the second line of research). Hence, this simulator-based effort will replicate the closed-course scenarios used previously. A second study of this simulator-based effort involves examining the CAMP Forward Collision Warning (FCW) timing/interface approach under more complex "surprise" (unexpected) braking scenarios than were examined in the previous CAMP FCW program (Kiefer et al., 1999). The intention is to develop surprise braking scenarios in the simulator that would be extremely difficult to replicate under closed-course conditions.

A second line of research of these four studies is aimed at evaluating and potentially refining the preliminary crash alert timing approach developed in the previous CAMP FCW program (Kiefer et al., 1999). This issue is addressed by employing the surrogate target (closed-course) methodology developed in this previous program, which is illustrated on the cover of this report. Surrogate target refers to the vehicle ahead of the driver's vehicle during a driving maneuver, or the lead vehicle. The "surrogate target" consists of a molded composite mock-up of the rear half of a passenger car mounted on an impact-absorbing trailer that is towed via a collapsible beam. The surrogate target provides a realistic crash threat to drivers under closed-course conditions, yet is able to absorb impacts of up to a 10 miles per hour velocity differential without sustaining permanent damage. Thus, the surrogate target methodology allows experimenters to safely place naive drivers in last-second braking, realistic rear-end crash scenarios on a closed test track and observe their behavior. Two studies will be conducted under this second line of research. The first study, which is the focus of the remainder of this paper, involves gathering additional data on driver's last-second maneuver behavior. The second study involves gathering additional data under surprise braking trial conditions, as well as under visual occlusion conditions.

The current study employs the surrogate target methodology to examine an expanded set of vehicle-to-vehicle kinematic conditions and scenarios (relative to those examined in the previous CAMP FCW program). This line of research will include approaches to a lead vehicle either moving at a constant speed or decelerating with more typical non-constant deceleration profiles. Finally, in the previous program drivers were asked to make "last second" braking maneuvers while approaching the surrogate target. In this line of research, the surrogate target methodology will be used for the first time to also examine "last second" steering (or lane-change) maneuvers.

The current study employed a methodology similar to that employed in Study 1 of the previous CAMP FCW program (Kiefer et al., 1999). In this previous study, 108 drivers were asked to perform "last second" braking maneuvers while approaching a slowing or stopped vehicle (surrogate target) without FCW system alerts. Drivers were instructed to use either "normal" or "hard" braking intensity during these last-second braking judgments. This strategy was taken so that drivers' perceptions of "normal" and "non-normal" kinematic situations (or envelopes) could be properly identified and modeled for crash alert timing purposes. The underlying assumption of this experimental strategy is that properly characterizing (i.e., modeling) the kinematic conditions surrounding hard braking onsets 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 assumption was validated in the previous CAMP FCW program.

In developing a FCW crash alert timing approach, two fundamental driver behavior parameters should be considered. These parameters serve as input into vehicle-to-vehicle kinematic equations that determine, given a set of assumptions, the alert range necessary to assist the driver to avoid a potential crash. The first driver behavior parameter is the time duration required for the driver to respond to the crash alert and begin braking, referred to as driver brake reaction time. (This reaction time assumption is added to other system delay times, such as interface delay times and brake system delay times.) This parameter was developed in Study 2, Study 3, and Study 4 of the previous CAMP FCW program (Kiefer et al., 1999) in which drivers experienced an unexpected rear-end crash scenario. The second driver behavior parameter needed for a crash alert timing approach is the driver deceleration (or braking) behavior in response to the FCW alert under a wide range of vehicle-to-vehicle kinematic conditions and scenarios. This parameter was also developed in the previous CAMP FCW program (Kiefer et al., 1999) under conditions in which an alerted driver made last-second braking judgments. This second parameter was developed in Study 1 of the previous CAMP FCW program (Kiefer et al., 1999), and is also the focus of the current study.

In accordance with the second line of research discussed above, the aim of the present study was to extend our current understanding of crash alert timing requirements (in particular, the driver deceleration parameter) to a broader range of driving scenarios employing the surrogate target methodology. Unlike previous work, the current study examined in-lane approaches to a lead vehicle moving at a slower but constant speed, as well as conditions where drivers were coached into following a lead vehicle at long (3-second) headways prior to executing the last-second driving maneuver. Hence, a primary goal of this study was to define when to present crash alerts in these new scenarios and to understand the extent to which the previous data CAMP FCW timing approach should be modified. In addition, unlike the previous CAMP FCW work that examined only last-second braking maneuvers, the current study also examined last-second steering maneuvers. For these latter lane change data, a primary goal was a comparison of last-second braking onsets versus last-second steering onsets under a variety of vehicle-to-vehicle kinematic conditions. This interest was based upon an important FCW implementation concern about whether an FCW alert timing approach based only on driver braking assumptions may annoy drivers that approach a lead vehicle with the intent to perform a lane-change maneuver around the vehicle (rather than remain in their current driving lane). Furthermore, these in-path nuisance alerts may be problematic in general or only under certain vehicle-to-vehicle kinematic conditions. Hence, it may be prudent to modify (or more specifically, delay) crash alert timing based on these lane change-nuisance alert considerations. Finally, this data was gathered at the Transportation Research Center is East Liberty, Ohio, unlike the previous CAMP FCW data which was gathered at the General Motors Milford Proving Ground test site in Milford, Michigan. Hence, comparisons could be made between these two data sets to ensure the pattern of findings were robust across test sites.

Method

Participants

Seventy-two participants were recruited from three age groups. The younger, middle-aged, and older groups ranged from 20 to 30, 40 to 50, and 60 to 70 years old, respectively. (Note these age groups were identical to those employed in the earlier Kiefer et al. (1999) work.) Each age group contained 12 males and 12 females. Each driver was tested individually in one 2 to 2 ½ hour session and paid $150 for their participation. Participants were recruited by telephone interview (via an outside marketing firm) from within the Columbus, Ohio metropolitan area. A participant information letter (shown in Appendix A) and informed consent release form (shown in Appendix B) were mailed to participants' homes prior to their scheduled test session. Participants were required to provide a completed, signed informed consent form prior to participation. Participants were given an opportunity to ask questions before signing the consent form.

All participants were required to possess a valid, unrestricted U.S. driver's license (except for corrective eyeglasses or contacts) and have a minimum of 2 years driving experience. Individuals with a history of heart condition, heart attack, stroke, epilepsy, chronic respiratory disorder, motion sickness, inner ear problems, vertigo, insulin-required diabetes, chronic migraines, and pregnant females were excluded from participation. Participants were recruited without bias regarding race, creed, gender, or national origin. Appendix C shows the participant screening background information questionnaire used in the telephone interview.

Subject Vehicle

The vehicle driven by the participant was the 1997 Ford Taurus SHO used in the first CAMP FCW project (Kiefer et al., 1999), referred to as the Subject Vehicle (or SV). The SV was instrumented to continuously record speed, longitudinal acceleration, lateral acceleration, yaw rate, range, range angle, steering angle, lane position, video of driver's face, forward scene and pedal area, and GPS time and position.

Two experimenters rode in the SV with the test participant. A test-driver experimenter (from the Transportation Research Center) rode as the front-seat passenger in the SV during all testing. This experimenter had access to a passenger-side brake to prevent collisions with the surrogate target. An auditory alarm issued over headphones signaled the test driver experimenter in situations when it was necessary to apply the brake to override the driver's braking. The primary experimenter rode in the back seat of the SV during all testing to instruct participants through the trials, and operate the data acquisition system.

Surrogate Target and Principal Other Vehicle

The surrogate target and Principle Other Vehicle (a second 1997 Ford Taurus SHO) were identical to those employed in the first CAMP FCW project (Kiefer et al., 1999). The Principle Other Vehicle (or POV) towed the surrogate target assembly. The surrogate target was a three-dimensional mock-up of a 1997 Mercury Sable rear end mounted on a lightweight trailer frame. The mock rear end was constructed of polyurethane with a thin, reinforcing fiberglass undercoat. The mock rear end was equipped with working brake lights. The trailer was modified with a high-density Styrofoam and coiled spring bumper. The mock rear end and trailer was attached to a 40-foot telescoping, tow-beam capable of collapsing approximately nine feet. During the experimental trials, the SV and POV data acquisition systems were networked using a LAN link. The experimenter in the SV controlled the beginning and end of a trial in both the SV and the POV. The POV speed and deceleration levels were controlled by the data acquisition system. The SV experimenter and the POV test drivers communicated during the study via digital radio communication.

Data Acquisition System

The data acquisition system was identical to that used in the first CAMP FCW project (Kiefer et al., 1999), with the exception of a few changes which were made to accommodate the recording of steering maneuvers. First, the single axis accelerometer was replaced with a 3-axis accelerometer. Second, a lane sensor was added but proved to provide unreliable lane position data during the rapid last-second lane changes observed. Consequently, as described below, the steering onsets were "hand marked". Third, the scanning range sensor also provided angle information to the target.

Test Track

The study was conducted on three adjacent lanes of a straight, level, six-lane skid pad located at the Transportation Research Center in East Liberty, Ohio. The lanes were 1,097 m in length and 4 m wide. All testing was conducted during dry road, daytime conditions.

Driving Scenarios

Three different general driving scenarios were choreographed for the study. In these scenarios, the driver in the SV was always approaching the surrogate target (towed by the POV) at a constant speed prior to last-second braking or steering. Furthermore, across these three different general driving scenarios, the surrogate target lead vehicle was either stationary, moving at a slower but constant speed, or decelerating to a stop. The following provides a more detailed description of each of these three distinct approach scenarios.

For the *POV Stationary Trials*, the surrogate target was stationary (or parked) in the center of its lane, three-quarters of the length from the beginning of the track. For trials when drivers were braking, the target was parked in the center lane of the three lanes, and the SV approached the target at either 30 or 60 MPH, staying in the center lane throughout the braking maneuver. For trials when drivers were steering (i.e., performing lane-change maneuvers), the target was parked in the right-most lane of the three lanes and the SV approached the target at either 30 or 60 MPH staying in the center of the right-most lane until making a lane change to the left into the center lane.

For the *Constant Delta V (ΔV) Trials*, the surrogate target traveled at a constant speed lower than that of the SV. The SV also traveled at a constant speed while closing on the target until the driver performed a braking or steering maneuver to avoid colliding with the target. The SV/POV speed combinations (in MPH) examined were 30/20, 30/10, 60/50, 60/30, and 60/15. These conditions correspond to ΔV conditions of 10, 20, 10, 30, and 45 MPH, respectively. For trials when drivers were braking, the target and SV both traveled in the center lane of the three lanes throughout the braking maneuver. For trials when drivers were steering, the target and SV both traveled in the right-most lane of the three lanes until the SV driver made a lane change to the left into the center lane. Unlike the POV Stationary Trials (described above) and the POV Decelerating Trials (described below), these trials were not examined in the earlier CAMP FCW work (Kiefer et al., 1999).

For the *POV Decelerating Trials*, the SV driver followed the POV in the travel lane. After traveling at a stabilized headway for a brief duration, the POV would brake at a constant deceleration of either –0.15 g's or –0.39 g's with the brake lights activated. The SV driver then performed a last-second braking or steering maneuver to avoid colliding with the target. These maneuvers were performed at 30 and 60 MPH. As with the POV Stationary Trials and Constant ΔV Trials, if drivers were braking, the target and SV traveled in the center lane throughout the maneuver. If drivers were steering, the target and SV traveled in the right-most lane until the SV driver changed lanes to the left. These trials were conducted under two different initial headway conditions. For the *POV Decelerating / Normal Headway Trials*, the driver followed at their "normal" following distance behind the target prior to POV deceleration. For the *POV Decelerating / 3-Second Headway Trials*, drivers were coached by the primary experimenter to follow at a 3-second time headway behind the target prior to POV deceleration. It should be noted that these "long headway" cases were not treated as "special" in the data set, but rather, were included to expand the previous CAMP FCW data set (which already included some driver-selected long headway cases) in order to ensure these cases are adequately represented in the data set.

Driving Maneuvers

All 72 participants performed both types of driving maneuvers in a subset of driving scenarios, last-second braking and last-second steering. The instructions for these two driving maneuvers were as follows.

Last-Second Braking

Drivers performed last-second braking maneuvers using two different braking instructions. The first instruction asked drivers to maintain their speed and brake at the last second possible in order to avoid colliding with the target using "normal" braking intensity or pressure. The second instruction asked drivers to maintain their speed and brake at the last second possible to avoid colliding with the target using "hard" braking intensity. These two instructions will be subsequently referred to as "normal braking" and "hard braking" instructions.

It should be noted that in Study 1 of the previous CAMP FCW human factors work (Kiefer et al., 1999), 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, of interest was when drivers perceive the need to begin braking. Second, it is anticipated that a driver's 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 that the braking distance and braking levels observed may be representative of a driver's hard braking levels in response to a crash alert. In the present work, it was decided not to discourage drivers from "second guessing" in order to allow possibly more natural braking behavior. Consequently, the observed braking distances in the current study are less useful because drivers often braked to a very low speed and then slowly coasted close to the lead vehicle at the end of the trial. As it turned out, the lack of difference reported below between the previous CAMP work relative to the current work suggests that braking onset was not affected by this change in instruction in an attempt to allow more naturalistic braking behavior.

Last-Second Steering

Drivers performed last-second steering (or lane change) maneuvers using two different steering instructions. The first instruction asked drivers to maintain their speed and change lanes at the last second they “normally would to go around the target”. The second instruction asked drivers to maintain their speed and change lanes at the last second they “possibly could to avoid colliding with the target”. These two instructions will be subsequently referred to as “*normal steering*” and “*hard steering*” instructions.

Experimental Procedure and Design

Upon entering the vehicle, participants were instructed to make themselves comfortable for driving by adjusting the seat, steering wheel, and mirrors as necessary. Participants then had an opportunity to become familiar with the handling characteristics of the vehicle during a short drive from the building area of the facility to the skid pad test area. Participants were then told about the general nature of the tasks they were to perform and that the surrogate target was designed to allow impacts.

Each participant performed both last-second braking and last-second steering maneuvers in selected driving scenarios. The numbers of participants performing the driving maneuvers for each driving scenario are shown in Table 1. Two “mini” studies were conducted. During both these studies, several vehicle-to-vehicle kinematic conditions were redundant with those tested in the previous CAMP work (conducted at the Milford Proving Ground in Milford, Michigan) for comparison purposes. For example, each subject experienced the CAMP surprise trials kinematic scenario (30 MPH driver speed/30 MPH lead vehicle speed /0.39 g lead vehicle deceleration) under alerted, normal (self-selected) headway conditions. In addition, more data was gathered under the normal (self-selected) headway condition than in the 3-second headway condition.

The first “mini” study, referred to as TRC-Study A, focused on the Constant ΔV Trials shown below, and the second “mini” study, referred to as TRC-Study B, focused on POV Decelerating and POV Stationary Trials. For each participant, trials were blocked on maneuver type (steering and braking) and instruction type (normal and hard). The order of trial blocks was counterbalanced across participants with the restrictions that blocks alternated between steering and braking and that normal headway trials were completed before long headway trials. The latter restriction was established after pilot testing revealed that instructing participants to long headway positions influenced their self-selected headway positions in the normal headway condition.

Driver Performance Measures

This analysis focused primarily on required deceleration and time-to-collision based measures at either the point of last-second braking onset or at the point of last-second steering onset. It should be noted that SV braking onset was <u>not</u> defined relative to the brake switch trigger point, since it was observed in the previous work that some drivers had a tendency to momentarily place their foot on the brakes during their last-second braking decision. Instead, as in the first CAMP FCW Project (Kiefer et al., 1999), SV braking onset was defined as the point in time in which the vehicle actually began to slow as a result of braking. More specifically, SV braking onset was defined as five 30 Hz data samples (or 165 ms) prior to SV crossing the 0.10 g deceleration level. (The reader is referred to the earlier Kiefer et al. work for the supporting rationale for this braking onset definition.)

A 2-step process was used to determine steering onsets. The first step involved using the recorded data stream (e.g., lateral acceleration) to find the lane change during the trial. Using this time stamp as a “gross” reference point, the second step involved a “frame-by-frame” video analysis of the view showing the driver’s hands on the steering wheel. The first instant the steering wheel moved in the direction of the subsequent lane change was then "time stamped", and later input into the data stream as the steering onset point.

Table 1. Number of Participants Performing Braking and Steering Maneuvers in Each Driving Scenario

Driving Scenario	Last-second Braking / Normal Headway	Last-second Braking / Long Headway	Last-second Steering / Normal Headway	Last-second Steering / Long Headway
POV Stationary				
30 MPH	54		36	
60 MPH	54		36	
Constant ΔV				
30/10	36		36	
30/20	36		36	
60/15	36		36	
60/30	36		36	
60/50	36		36	
POV Decelerating				
30/30/-0.15	30	18	18	18
30/30/-0.39	54	18	18	18
60/60/-0.15	30	18	18	18
60/60/-0.39	30	18	18	18

Various performance measures were analyzed, each of which is defined below. Most of these measures are derived from the SV speed, POV speed, SV acceleration, POV deceleration, and/or range (between vehicles) measures, which were recorded at 30 Hz.

The *required deceleration* measure was defined as the constant deceleration level (in g's) required for the driver to avoid colliding with the lead vehicle at the point of braking or steering onset. This measure was calculated by assuming the prevailing driver (SV) speed and lead vehicle (POV) speeds, and assuming the lead vehicle continued to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing) until it came to a stop (at which point it remained stopped). The reader is referred to the previous CAMP FCW work for a more detailed description of this measure (Kiefer et al., 1999). It should be noted that the required deceleration measure was shown in the previous CAMP FCW work to be tightly coupled to the fundamental kinematic variable, braking (or stopping) distance.

Three different time-to-collision (or TTC) measures were examined at braking or steering onset. These measures are expressed in seconds. Each of these measures assumes the lead and following drivers maintain "straight ahead" (collision-course) trajectories. Unlike the required deceleration measure, these time-based measures do not provide a direct linkage to stopping distance.

The *TTC-Case 1* measure was defined as the time it would take the following and lead vehicle to collide assuming the prevailing following vehicle speed and lead vehicle speed. This is mathematically defined as the range between the two vehicles divided by the difference in speeds between these two vehicles, or Range/ΔV. Note that with this measure the lead vehicle and following vehicle speeds are assumed to remain constant throughout the maneuver, and that the current decelerations of either vehicle are irrelevant to the TTC-Case 1 calculation. This measure is sometimes referred to as "momentary TTC".

The *inverse TTC-Case 1* measure was simply defined as the inverse of TTC-Case 1, or ΔV/Range. The rationale for exploring this measure was two-fold. First, as will be discussed later, the inverse TTC-Case 1 measure appears in the time derivative of required deceleration, which corresponds to how fast required deceleration is changing per unit time. Second, earlier work by Evans and Rothery (1974) found this measure to be the most robust measure (of those evaluated) for describing driver's relative motion judgments (judging whether they were closing or "opening" relative to the lead vehicle) under in-traffic conditions with extremely small relative speed/acceleration values.

The *TTC-Case 2* measure was defined as the time it would take the following and lead vehicle to collide assuming the prevailing following vehicle speed and lead vehicle speed, as well as assuming the following vehicle acceleration is zero and that the lead vehicle continues to decelerate at the prevailing deceleration value (i.e., at the current "constant" rate of slowing) until it comes to a stop (at which point it remains stopped). This measure is equivalent to TTC-Case 1 for POV Stationary Trials and Constant ΔV Trials, but differs from TTC-Case 1 for POV Decelerating Trials. It should be noted that in calculating both the TTC-Case 2 and required deceleration measures during POV Decelerating Trials, the movement state of the lead vehicle (stationary or moving) during the "playing out" of the lead vehicle speed and braking assumptions was addressed.

Overall, it should be noted that the required deceleration and TTC-Case 2 measures provide more direct measures of actual crash risk than the TTC-Case 1 and inverse TTC-Case 1 measures, since the former measures use the measured (real-time) lead vehicle deceleration values. However, the TTC-Case 1 based measures are worthwhile to explore for two reasons. First, from an implementation perspective, measuring lead vehicle deceleration in an accurate, real-time fashion provides a difficult technology challenge given the current state-of-the-art in FCW sensing. Second, to the extent that drivers are not able to effectively estimate lead vehicle deceleration and/or fail to use this information in making last-second maneuver decisions, the TTC-Case 1 and inverse TTC-Case 1 measures may prove to be important from a driver behavior and mental model perspective.

Results and Discussion

Description of Observed Last-Second Braking Onsets and Last-Second Steering Onsets

Study, Age, and Gender Effects

In order to investigate Age (young, old), Gender (male, female), and Study (CAMP-Study 1, TRC-Study A, TRC-Study B) effects, mixed Analyses of Variance (ANOVAs) were performed separately for each of the 17 vehicle-to-vehicle kinematic conditions examined in the current and previous CAMP data set (Kiefer et al., 1999). A *kinematic condition* refers to the SV speed/POV Speed/POV deceleration combination, where speeds are expressed in MPH and the deceleration value is expressed in g's (e.g., 30 / 30 / 0.39). For each kinematic condition, the following three factors were included in the ANOVA: Age (20-30, 40-50, 60-70 years), Gender (male, female) and Instruction (normal, hard). In addition, Maneuver Type (steering, braking) was included in the ANOVA for the 11 of the 17 kinematic conditions where both last-second braking and last-second steering data were available (30/30/0.15, 30/30/0.39, 60/60/0.15, 60/60/0.39, 30/10/0, 30/20/0, 60/15/0, 60/30/0, 60/50/0, 30/0/0, 60/0/0). Finally, Study was also included as a factor in the ANOVA for the 6 of the 17 kinematic conditions under which last-second braking data were obtained across studies (30/30/0.15, 30/30/0.39, 60/60/0.15, 60/60/0.39, 30/0/0, 60/0/0). The required deceleration measure was employed to examine these effects, and all statistically significant effects reported below at least met the $p<0.01$ criterion (unless otherwise indicated).

Overall, there were very few significant effects involving the Study variable. Only 1 of 6 possible main effects was found, and this main effect was relatively small in magnitude. For the 30/0/0 kinematic condition, the mean required deceleration for this condition in CAMP-Study 1, TRC-Study A, and TRC-Study B were 0.24, 0.22, and 0.21 g's respectively. There was also Study by Instruction interaction effects for 4 of the 6 possible kinematic conditions (30/30/0.39, 60/60/0.15, 60/60/0.39, 60/0/0). These interaction effects appeared to be primarily due to different patterns of results across studies in the hard braking instruction condition, where last-second maneuver onsets were generally most aggressive (occurred later, closer to the lead vehicle) in CAMP Study 1 and generally least aggressive for TRC-Study B. Once again, these effects were generally small in magnitude. There are numerous reasons for the observed study differences, including differences in test participants, test track, test drivers, and types of kinematic conditions and maneuvers subjects experienced. Furthermore, there is no inherent reason why any of these data sets would be expected to be closer to the "truth". In addition, analyses conducted to compare the effect of "weighted" versus "unweighted" data sets on modeling results suggest differences across studies were inconsequential. Hence, given all these reasons, and the finding that the observed Study effects were generally small in magnitude, the current data set was pooled together with the previous Kiefer et al. (1999) Study 1 data for subsequent data analysis and data presentation purposes. Also, as was noted earlier, it appears braking onsets were not affected by the slight difference in braking instruction in this work relative to the braking instruction used in the earlier Kiefer et al. study. Unlike the braking instructions in the current work, drivers in the earlier Kiefer et al. study were discouraged from "double-pumping" or second-guessing their braking onsets.

Overall, there were also very few significant effects involving the Age variable. Only 2 of 17 possible main effects were found, and these effects for the 60/30/0 and 60/0/0 conditions were relatively small in magnitude. For the 60/30/0 condition, the mean required deceleration for the young, middle-aged, and older drivers were 0.20, 0.18, and 0.16 g's, respectively. For the 60/0/0 condition, the mean required deceleration for the young, middle-aged, and older drivers were 0.39, 0.37, and 0.35 g's, respectively. It should be noted there were also 4 marginally significant (p<0.05) main effects of Age for the 45/45/0.39, 60/60/0.39, 30/0/0, and 45/0/0 conditions, which also indicated more aggressive (i.e., later) brake onsets for the younger relative to older age group.

Main effects of Gender were observed for 6 of 17 possible kinematic conditions (30/30/0.39, 45/45/0.39, 60/60/0.15, 60/50/0, 30/0/0, 60/0/0). These effects were relatively small in magnitude (with 0.03 g's being the largest observed difference in mean required decelerations), and consistently indicated more aggressive brake onsets for the male relative to the female group. There was also Gender by Instruction interaction effects for 3 of the 17 possible kinematic conditions (60/60/0.15, 30/0/0, 60/0/0), as well as 4 corresponding marginally significant (p<0.05) Gender by Instruction effects (30/30/0.15, 30/30/0.39, 30/20/0, 30/10/0). These interaction effects appear to be primarily due to different patterns of results across studies in the hard braking instruction condition, where male maneuver onsets were generally somewhat more aggressive than female maneuver onsets (with differences across conditions ranging from 0.02-0.06 g's).

Given the effects of Age and Gender were not robust, and the observed effects are relatively small in magnitude, separate brake onset models were not created based on age or gender. Consequently, with an eye toward creating a crash alert timing model, the interactions of the more kinematic-oriented variables (described next) are of primary interest.

Higher-Order Interactions Between Kinematic Variables: 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 at last-second braking and last-second steering onsets. These variables play a fundamental role in determining crash alert timing. For POV Stationary Trials and Constant ΔV Trials, these key kinematic-oriented variables include speed (30, 45, 60 MPH), maneuver type (steering, braking), and instruction (normal, hard). For POV Decelerating Trials, these key kinematic-oriented variables include speed (30, 45, 60 MPH), maneuver type (steering, braking), instruction (normal, hard), and POV braking profile (0.15, 0.28, 0.39 g's).

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 allows the reader to make clean, straightforward comparisons across performance measures. Furthermore, in order to facilitate comparisons between data obtained across POV Decelerating Trials, Constant ΔV Trials, and POV Stationary Trials, data from the corresponding "highest order" interactions under these three different 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*". These kinematic figures represent a key strategy for representing and interpreting this large data set.

An example of a Kinematic Figure is shown in Figure 1 for the required deceleration measure. In each of these Kinematic Figures, the performance measure is shown on the vertical axis, and the various kinematic conditions are shown on the horizontal axis. The kinematic conditions associated with the POV Decelerating Trials, Constant ΔV Trials, and POV Stationary Trials are shown on the left-hand, central, and right-hand portions of the Kinematic Figures, respectively. It should be noted that although data from last-second braking show connected points within each of the three different types of trials, data points from last-second steering remains unconnected for POV Decelerating Trials and POV Stationary Trials, since these trials were not run at 45 MPH speeds or at the moderate (0.28 g) POV deceleration level. The number of drivers contributing to each data point is shown in Figure 2, which includes data from Study 1 of the previous CAMP FCW project (Kiefer et al., 1999). In total, each Kinematic Figure represents data from 4,326 last-second maneuver trials, including 3,536 last-second braking judgment trials and 790 last-second steering judgment trials.

The kinematic figure corresponding to the mean required deceleration measure is shown in Figure 1. The following data patterns are noteworthy.

First, the braking onset data from the "normal" braking conditions are less aggressive (i.e., the braking onsets occur earlier) than that obtained from the corresponding "hard" braking conditions. Similarly, the data from the "normal" steering conditions are less aggressive than those obtained from the corresponding "hard" steering conditions.

Second, the last-second steering onsets tend to be more aggressive than last-second braking onsets in the 60 MPH speed conditions (with the exception of the 60/50/0 condition), and this difference tended to increase as ΔV increased. (In the 30 MPH speed condition, the steering and braking onsets are quite comparable.) This difference between last-second steering and braking onsets were relatively substantial at differential speeds of 45 MPH and above. This overall pattern of results is also shown in Table 2, which shows for each kinematic condition the number of subjects in which last-second "hard" braking onsets occurred prior to last-second "hard" steering onsets. These differences clearly indicate that the relative timing of last-second braking onsets versus last-second steering onsets is highly dependent on the kinematic conditions. This suggests an alert timing approach based only on last-second braking considerations could result in alerts occurring prior to intentional lane change maneuvers under these conditions (this is addressed further in the "early" predicted brake onset analysis used when comparing models below).

Third, under both last-second "hard" steering and "hard" braking onset conditions, data from the Constant ΔV Trials are less aggressive than those obtained under POV Decelerating Trials and POV Stationary Trials when controlling for ΔV at last-second maneuver onset (e.g., 60/30/0 versus 30/0/0, or 60/15/0 versus 45/0/0).

Fourth, and more generally, the range of variation in mean required deceleration across these kinematic conditions is substantial, ranging from 0.07 to 0.50 g's in the "hard" instruction conditions. As was argued in the previous CAMP FCW work (Kiefer et al., 1999), these results provide strong evidence against a crash alert timing approach that assumes a fixed driver deceleration value (e.g., 0.30 g's) across kinematic conditions. Such a "fixed deceleration" approach is likely to results in predictions of the driver deceleration parameter which are perceived by the driver as either too late (i.e., the value desired by drivers is more aggressive than the assumed fixed value) or too early (i.e., the value desired by drivers are less aggressive than the assumed fixed value) under a wide range of vehicle-to-vehicle kinematic conditions. The corresponding standard deviations to the mean required decelerations shown in Figure 1 are shown in Figure 3. Overall, the same pattern of results was found, suggesting the variability of brake onsets increase as the required deceleration at brake onset increases.

<u>Figure 1</u>. Mean "Normal" and "Hard" Required Decelerations at Last-Second Braking Onset and Last-Second Steering Onset for Each Kinematic Condition

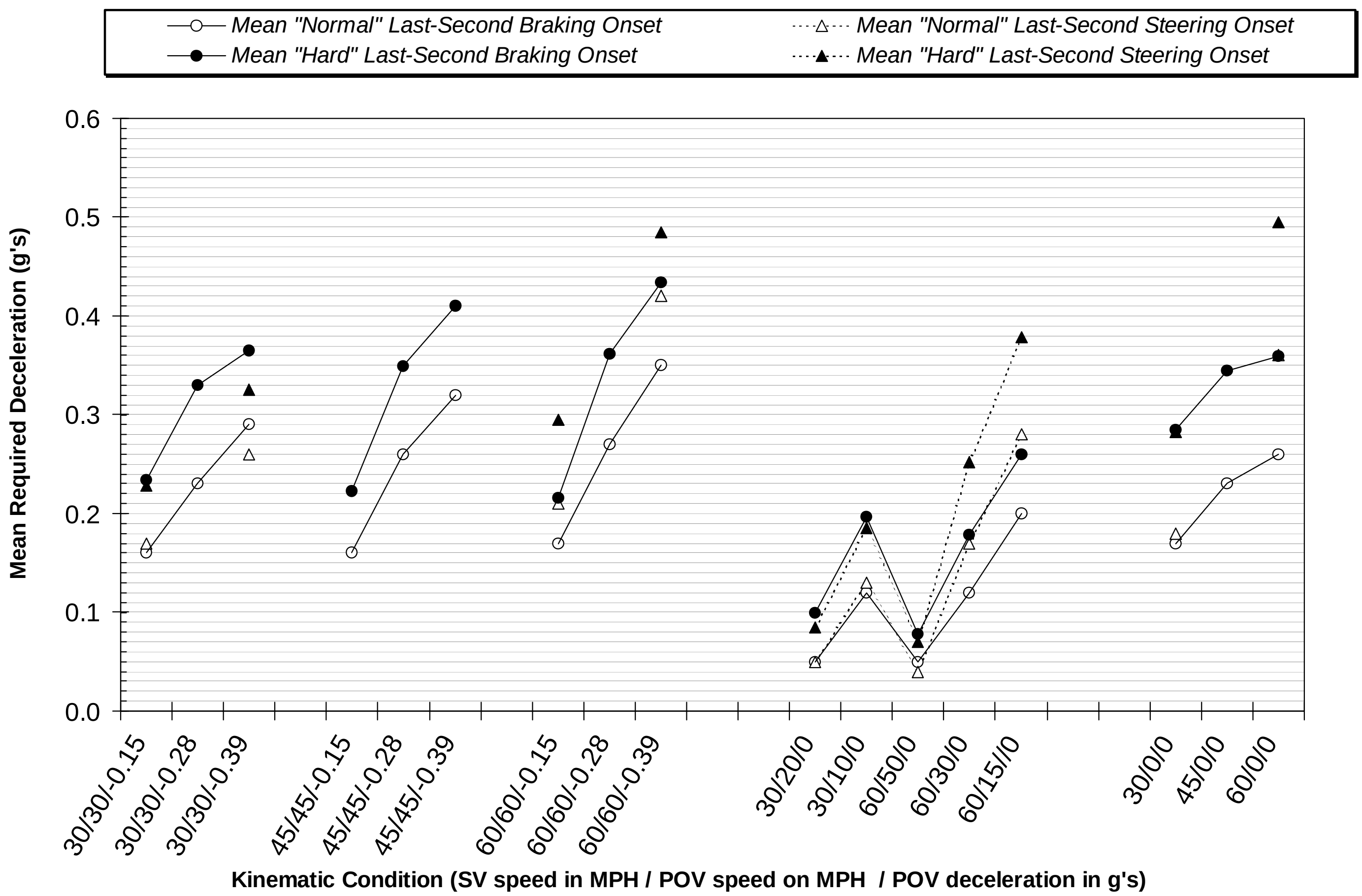
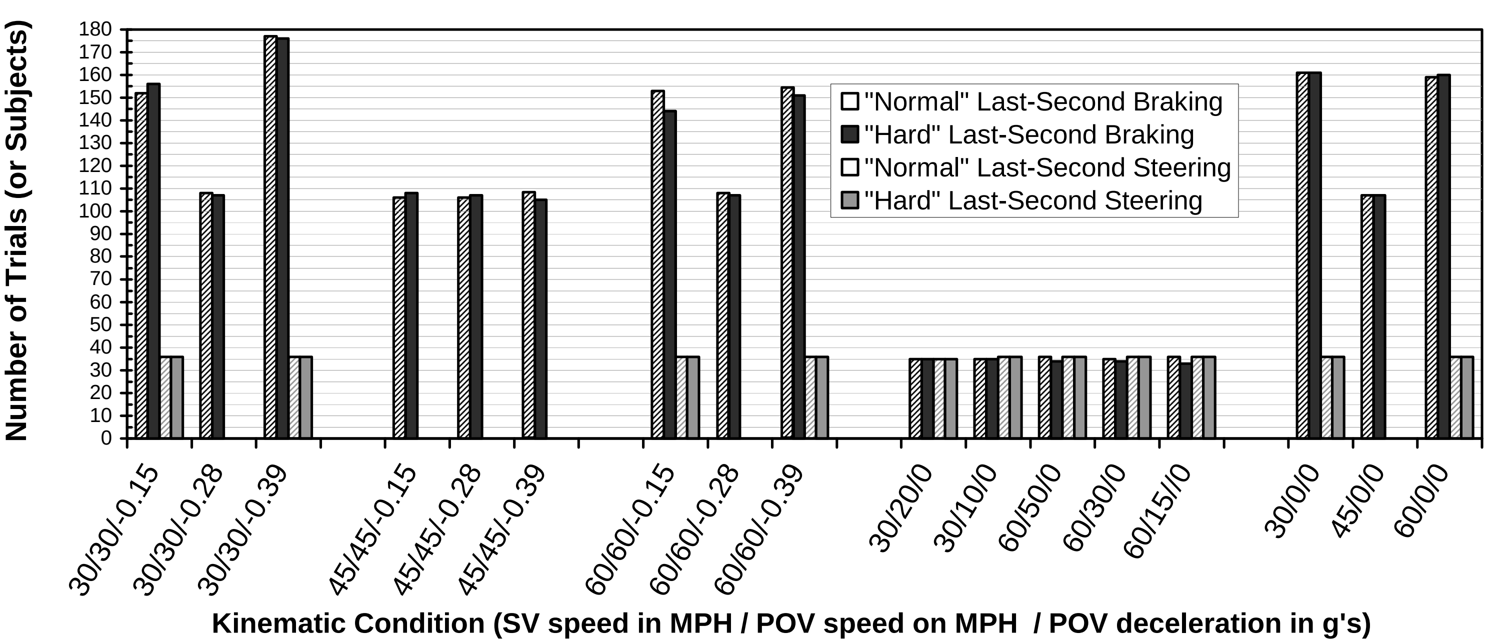


Table 2. Number of Subjects for Each Kinematic Condition in Which Last-Second "Hard" Braking Onsets Occurred Prior/After Last-Second "Hard" Steering Onsets Based on the Required Deceleration Measure

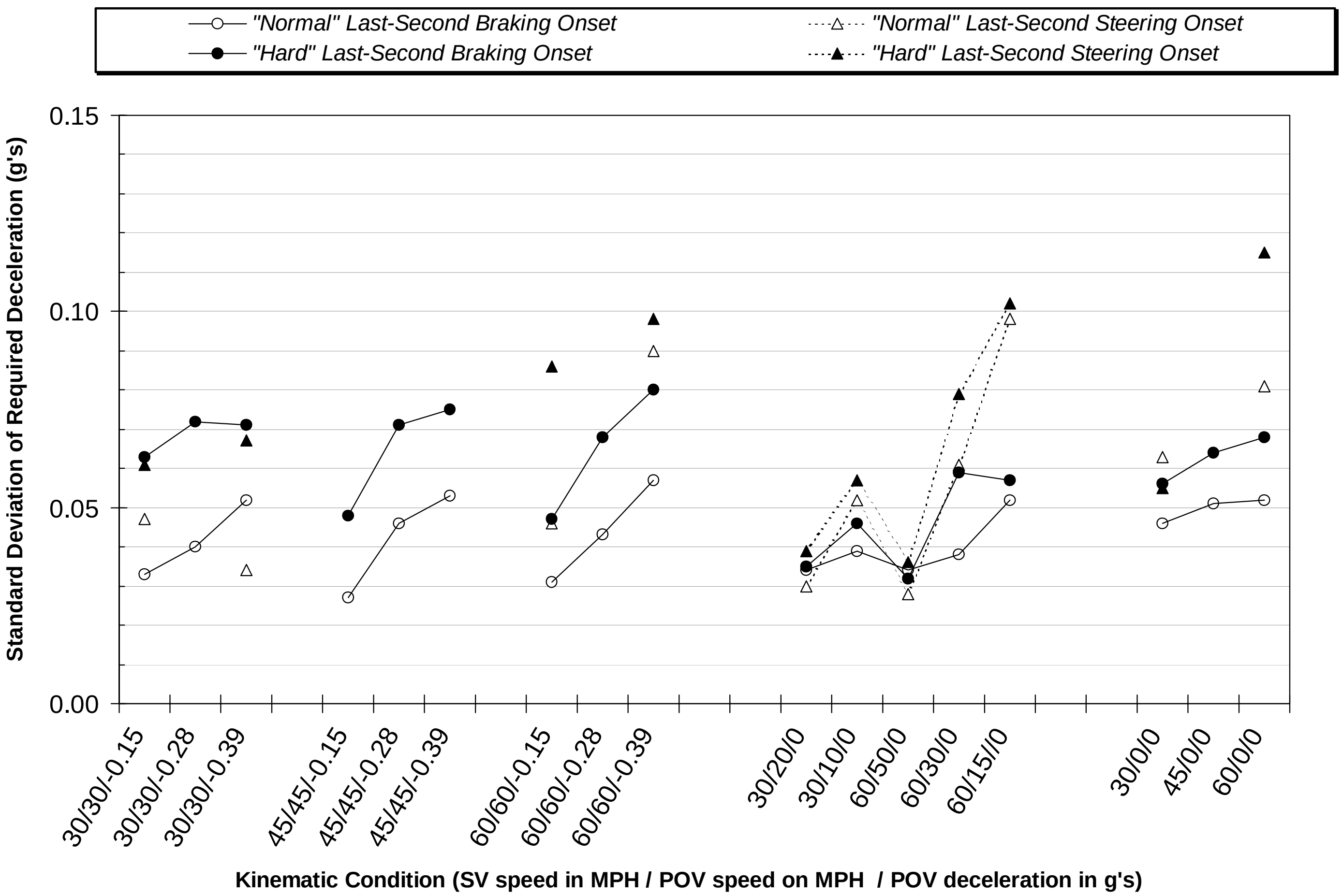
	Based on Required Deceleration Measure, Number of Subjects in Which….	
Kinematic Conditions SV speed (mph)/POV speed (mph)/POV decel. (g)	Last-Second "Hard" Braking Onset Occurred Prior to Last-Second "Hard" Steering Onset	Last-Second "Hard" Braking Onset Occurred After Last-Second "Hard" Steering Onset
30/30/-.15 *	5	13
30/30/-.39 *	4	14
60/60/-.15 *	16	1
60/60/-.39 *	13	5
30/20/0	11	23
30/10/0	12	23
60/50/0	14	20
60/30/0	30	4
60/15/0	30	3
30/0/0	21	15
60/0/0	35	1

Note: * Indicates data was based on "normal headway" rather than "3-Second" headway condition.

Figure 2. **Total Number of "Normal" and Hard" Last-Second Braking and Steering Trials Conducted Across the 17 Kinematic Conditions With MPG and TRC Data Combined (*which corresponds to the number of subjects tested in each kinematic condition*)**



<u>Figure 3</u>. Corresponding Standard Deviations to Mean "Normal" and "Hard" Required Decelerations at Last-Second Braking Onset and Last-Second Steering Onset for Each Kinematic Condition

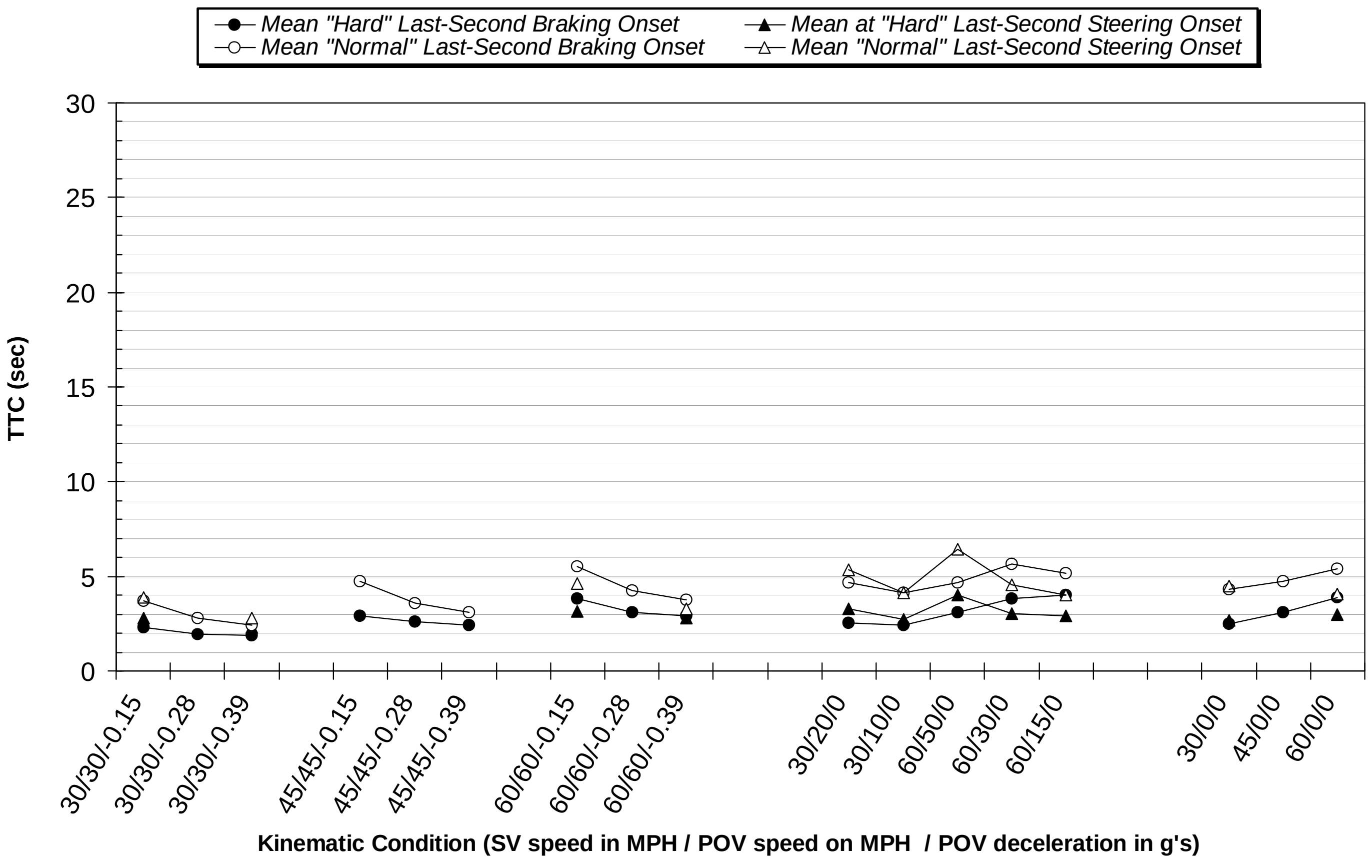


The kinematic figure corresponding to the mean TTC-Case 2 measure is shown in Figure 4. The overall data patterns, as expected, are nearly identical to those reported above for the required deceleration measure, since both measures are calculated with the identical sets of inputs.

The kinematic figure corresponding to the mean TTC-Case 1 measure is shown in Figure 5. The overall data patterns are similar, although not identical, to those reported above for the required deceleration and TTC-Case 2 measures (recall, unlike these latter measures, TTC-Case 1 does not use lead vehicle deceleration as an input). First, the braking onset data from the "normal" braking conditions are less aggressive than those obtained from the corresponding "hard" braking conditions, and this difference appears to sharply increase as POV deceleration (or braking level) decreases. The data from the "normal" steering conditions are less aggressive those obtained from the corresponding "hard" steering conditions, but (unlike for braking) this difference does not appear to sharply increase as POV deceleration (or braking level) decreases. Second, the last-second steering onsets tend to be slightly more aggressive than last-second braking onsets at the 60 MPH speed condition (with the exception of the 60/50/0 condition). (Once again, in the 30 MPH speed condition, the steering and braking onsets are quite comparable.) Unlike the required deceleration and TTC-Case 2 measures, in this 60 MPH speed condition, the separation between steering and braking onsets does not increase with the ΔV at braking onset, and instead remains relatively stable. Third, overall for both steering and braking conditions, data from the Constant ΔV Trials is slightly less aggressive than that obtained under POV Decelerating Trials and POV Stationary Trials when controlling for ΔV at braking onset (e.g., 60/30/0 versus 30/0/0, or 60/15/0 versus 45/0/0). Fourth, relative to the TTC-Case 2 measure (shown in Figure 4), the range in the mean TTC-Case 1 measures across kinematic conditions is substantially higher (about a 2-7 second range in the mean TTC-Case 2 values versus about a 2-27 second range in the mean TTC-Case 1 values). Note that this range difference between TTC-Case 1 and TTC-Case 2 is due to results found under POV Decelerating Trials, since TTC-Case 1 is equivalent to TTC-Case 2 for both Constant ΔV Trials and POV Stationary Trials.

The kinematic figure corresponding to the mean inverse TTC-Case 1 measure is shown in Figure 6. Once again, the overall data patterns are similar, although not identical, to those reported above for the required deceleration and TTC-Case 2 measures. First, the braking onset data from the "normal" braking conditions are less aggressive than those obtained from the corresponding "hard" braking conditions, and like the TTC-Case 1 measure, this difference increases as POV deceleration decreases for both the braking and steering data. Second, the last-second steering onsets tend to be more aggressive than last-second braking onsets at the 60 MPH speed condition (with the exception of the 60/50/0 condition). Unlike TTC-Case 1 (as well as the Required Deceleration and TTC-Case 2 measures), this effect is reversed in the 30 MPH speed condition, whereby last-second braking onsets are more aggressive than last-second steering onsets. Unlike the required deceleration and TTC-Case 2 measures, in this 60 MPH speed condition, the separation between steering and braking onsets does not show a clear increase with the ΔV at braking onset. Third, overall for both steering and braking conditions, data from the Constant ΔV Trials is slightly less aggressive than that obtained under POV Decelerating Trials and POV Stationary Trials when controlling for ΔV at braking onset (e.g., 60/30/0 versus 30/0/0, or 60/15/0 versus 45/0/0).

Figure 4. Mean "Normal" and "Hard" TTC-Case 2 at Last-Second Braking Onset and Last-Second Steering Onset for Each Kinematic Condition



<u>Figure 5</u>. Mean "Normal" and "Hard" TTC-Case 1 at Last-Second Braking Onset and Last-Second Steering Onset for Each Kinematic Condition

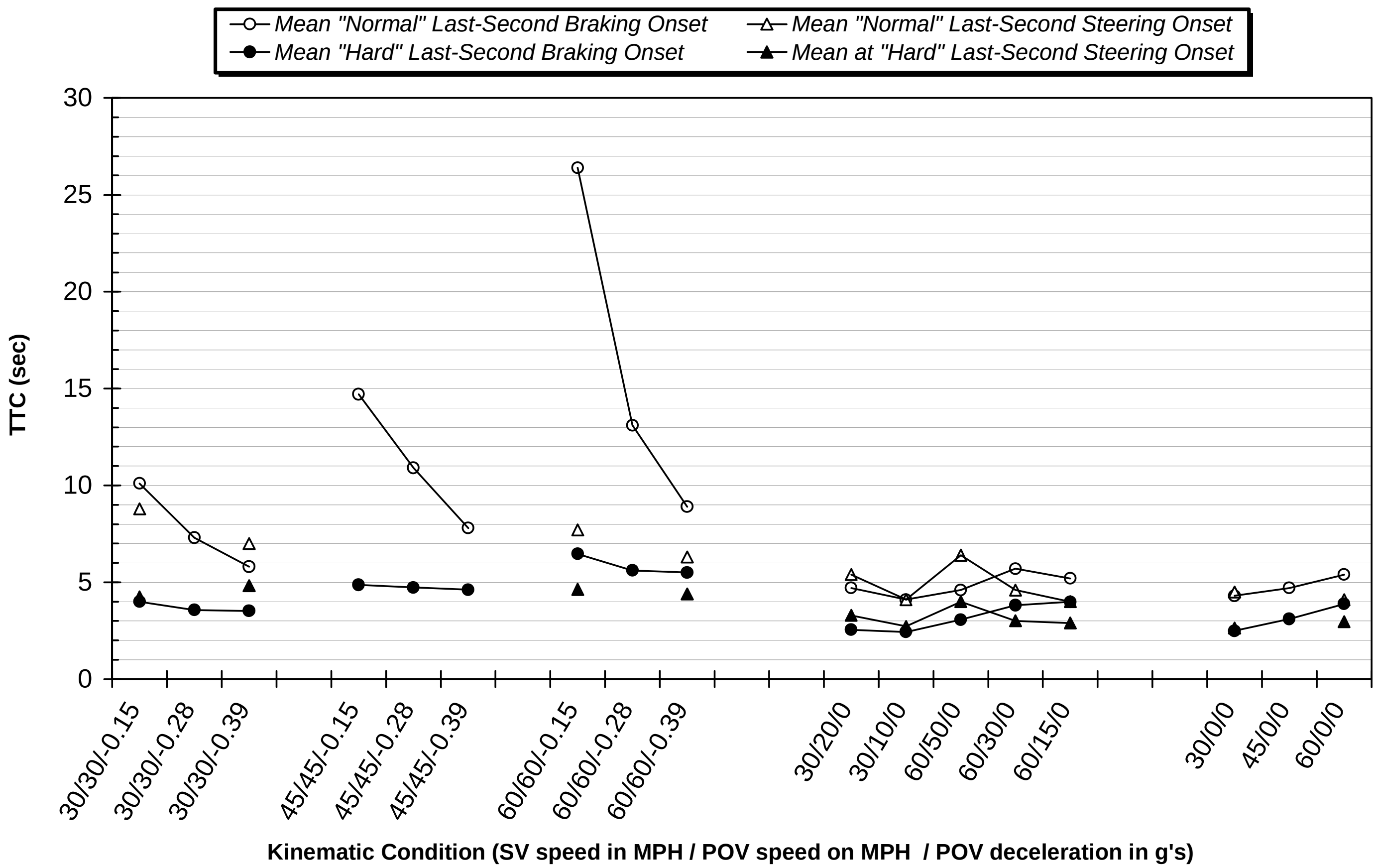
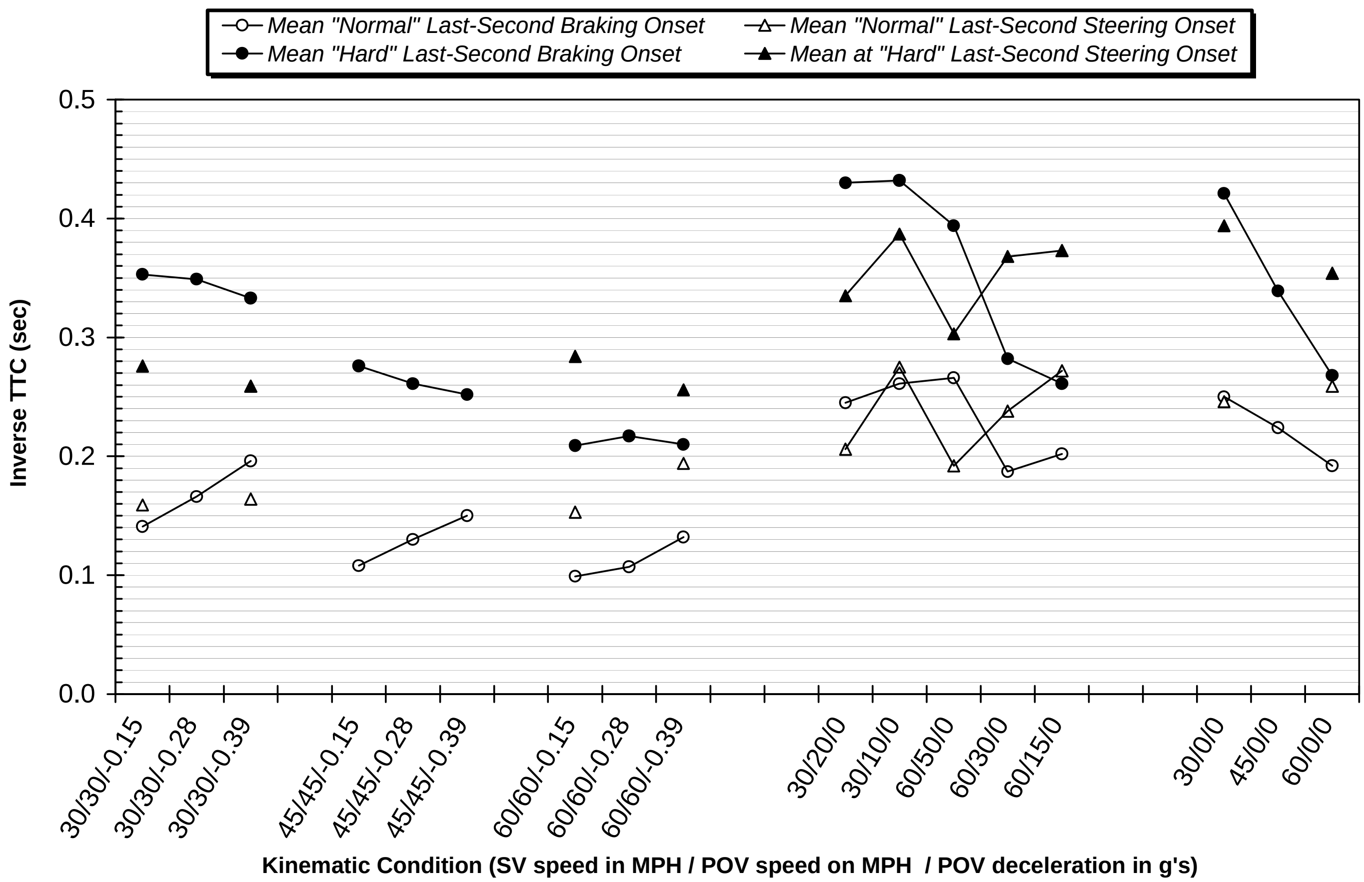


Figure 6. **Mean "Normal" and "Hard" Inverse TTC-Case 1 at Last-Second Braking Onset and Last-Second Steering Onset for Each Kinematic Condition**



Coefficient of Variation "Stability Analysis"

In order to give the reader a sense of the relative stability of these four measures (required deceleration, TTC-Case 2, TTC-Case 1, and inverse TTC-Case 1), coefficient of variation (or COV) measures were calculated for the "hard" instruction condition. The COV is defined for a given measure as the standard deviation divided by the mean (standard deviation/mean). The COV has the advantage of comparing across measures on the same "normalized" scale. For each of the four measures, the COV measure was calculated for both the braking and steering data for each of the 17 kinematic conditions. To the extent that a measure is stable within a kinematic condition across drivers (i.e., the COV is low), the measure offers the advantage that there is less spread or variation surrounding the mean values, and hence, differences between observed versus predicted results during modeling may be minimized. Results from this approach for last-second braking and last-second steering maneuvers are shown in Figure 7 and Figure 8, respectively. The data from last-second braking and last-second steering trials suggest, overall, that the required deceleration and TTC-Case 2 measures seem to remain more stable relative to the other measures when the lead vehicle is braking. Perhaps more interestingly (for reasons which will become clear later in the paper), these data also suggest that the inverse TTC-Case 1 measure remains more stable than the TTC-Case 1 measure (recall the former measure is a non-linear transformation of the latter measure), and is quite comparable to the TTC-Case 2 and required deceleration measure when the lead vehicle is not braking.

Peak Decelerations During Last-Second Lane Changes

In order to provide the reader with a sense of driver's aggressiveness during last-second lane change maneuvers, Figure 9 provides mean peak lateral accelerations and 90th percentile peak lateral accelerations for each of the 11 kinematic conditions under which lane change maneuvers were conducted. As was noted above, the data from the "normal" steering conditions are less aggressive than those obtained from the corresponding "hard" steering conditions. Interestingly (unlike for the other measures reported above), data from the Constant ΔV Trials are very similar to those obtained under POV Stationary Trials when controlling for ΔV at braking onset (e.g., 60/30/0 versus 30/0/0, or 60/15/0 versus 45/0/0).

Modeling Results: Development of the Two Modeling Approaches

Characterizing the Database Modeled

The modeling efforts were primarily focused on the last-second braking onset data, although the last-second, "normal" steering data were used for calculating "early" brake onset rates (which will be discussed later). The reader is reminded that out of the 4,326 last-second maneuver trials conducted over the current and previous CAMP data sets (Study 1 of Kiefer et al., 1999), 3,536 (or 82%) of these trials involved last-second braking judgments and 790 (or 18%) of these trials involved last-second steering judgments. Within each maneuver type (braking, steering), approximately half of these trials were conducted under last-second "normal" instruction conditions, and approximately half of these trials were conducted under last-second "hard" instruction conditions. Furthermore, it should be noted that current study contributed 1,746 last-second maneuver trials to the data set, of which 956 involved last-second braking (which amounts to 27% of the entire last-second braking data set). (Not included in these totals are trials which were not available for analysis due to equipment problems, which corresponded to 3% of the trials conducted.)

Figure 7. Coefficient of Variation (*standard deviation/mean*) for Various Measures for "Hard" Last-Second Braking Trials

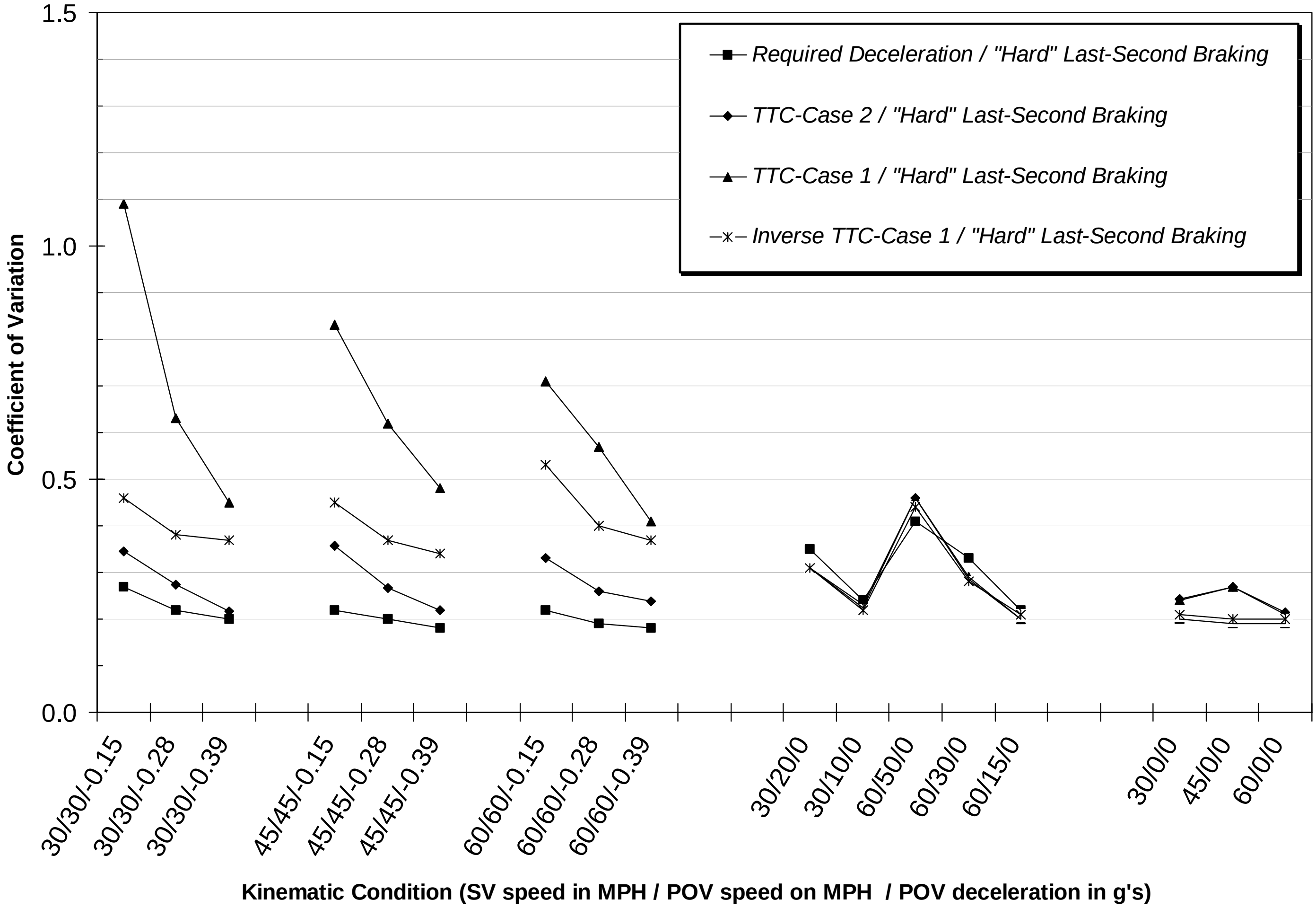


Figure 8. Coefficient of Variation (*standard deviation/mean*) for Various Measures for "Hard" Last-Second Steering Trials

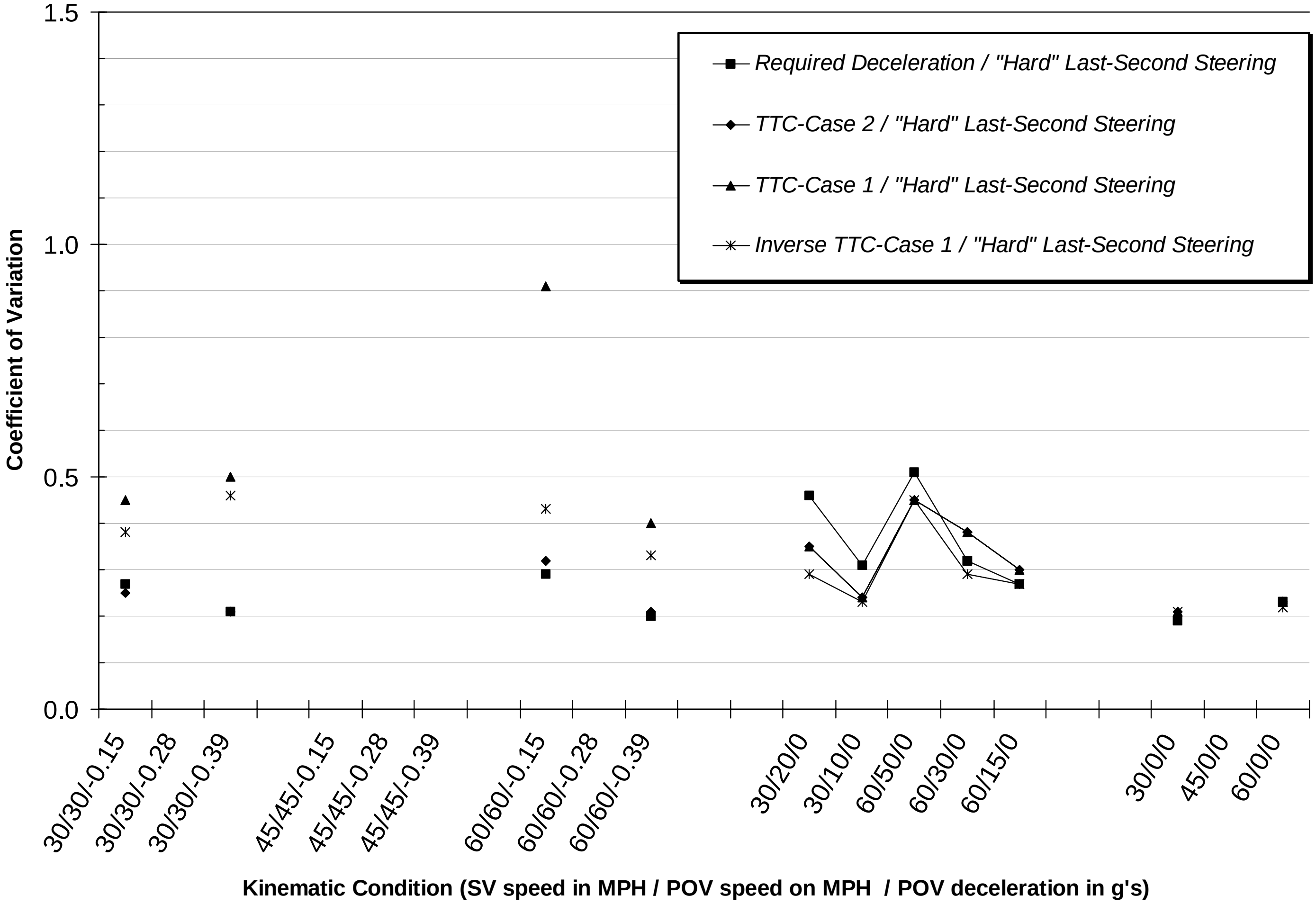
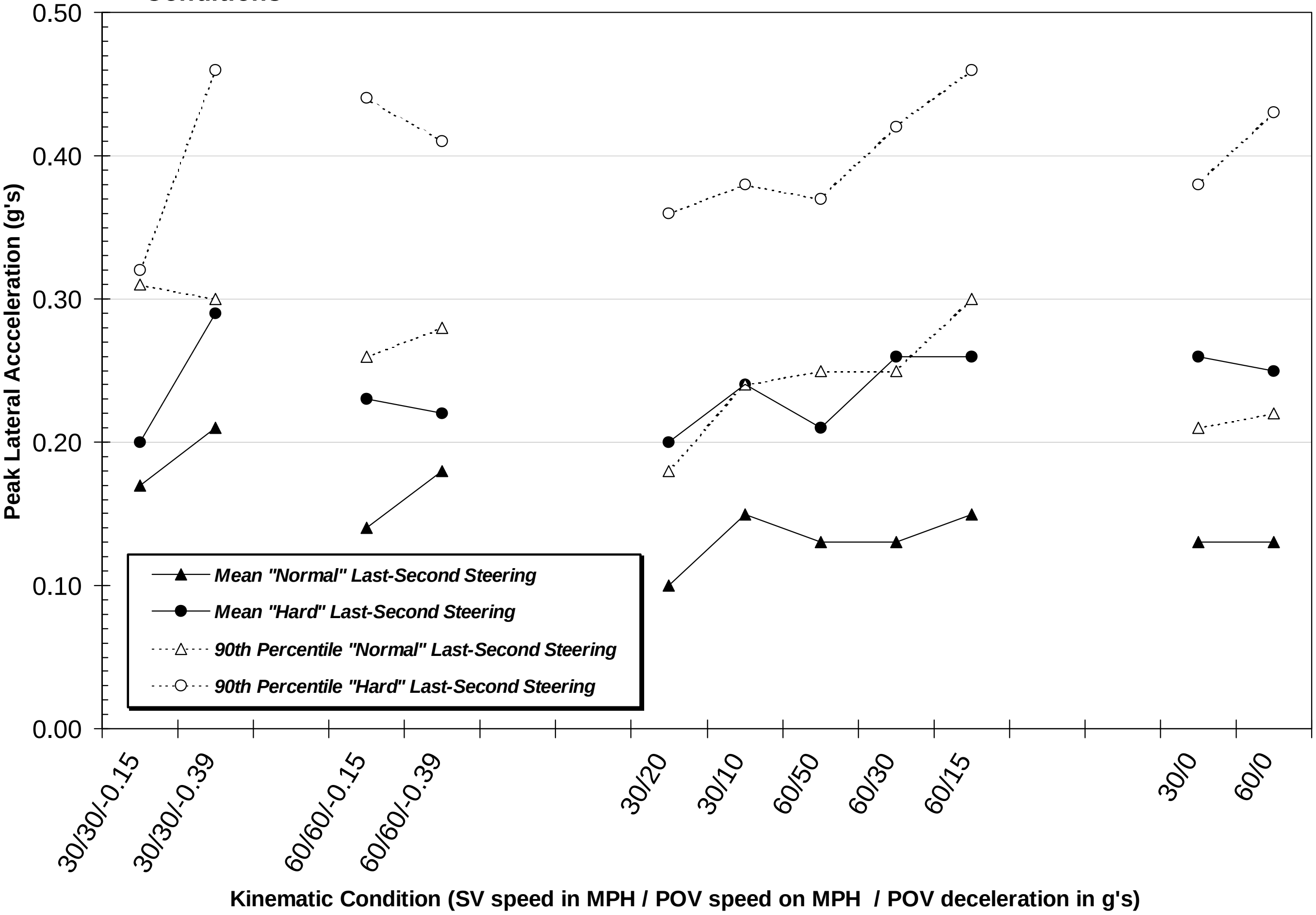


Figure 9. Mean and 90th Percentile Peak Lateral Accelerations under "Normal" Headway Conditons During Last-Second Steering Maneuvers Across Kinematic Conditions



Of the last-second braking trials conducted, POV Decelerating Trials, Constant ΔV Trials, and POV Stationary Trials represent 66%, 10%, and 24% of the database, respectively. Furthermore, with respect to driver speed, 30 MPH, 45 MPH, and 60 MPH trials represent 38%, 24%, and 38% of the last-second braking trial database, respectively. A more detailed breakdown of the last-second braking trials database was shown earlier in Figure 2.

Due to the relatively limited number of steering (relative to braking) trials conducted, and the more limited number of different vehicle-to-vehicle kinematic conditions examined during steering relative to braking trials (see Figure 2), only limited attempts were made to model the steering data. These limited attempts tended to suggest a last-second steering model which was more consistent with the 3-Tiered Inverse TTC Model than the New Required Deceleration Model. Both of these models will be discussed in great detail later in the paper. A description of the limited efforts to model the last-second steering data can be found in Appendix D.

General Modeling Approach.

The goal of this modeling effort is to effectively model driver deceleration (or braking) behavior in response to the FCW alert under a wide range of vehicle-to-vehicle kinematic conditions and scenarios. Recall, that this driver deceleration parameter, along with the driver brake RT parameter, are the two fundamental driver behavior parameters which should be considered in a crash alert timing approach. These parameters serve as input into vehicle-to-vehicle kinematic equations that determine, given a set of assumptions, the alert range necessary to assist the driver to avoid a potential crash.

Two different statistical approaches were employed in modeling the data set, linear regression and logistic regression. Linear regression uses a set of predictor variables to estimate a continuous dependent variable. In this case, linear regression was used to predict last-second, hard braking onset given a specific vehicle-to-vehicle kinematic scenario. Note that only the "hard" braking instruction data is used directly in the statistical modeling process. (The "normal" braking data is used indirectly, which will be explained shortly). In contrast, logistic regression uses a set of predictor variables to estimate a binary dependent (or binary outcome) variable. In this case, the binary outcome was whether or not a specific vehicle-to-vehicle kinematic braking onset scenario was a "normal", last-second braking onset scenario or a "hard", last-second braking onset scenario. Logistic regression was used to predict the probability of hard braking onset given a specific vehicle-to-vehicle kinematic scenario. In contrast to the linear regression approach above, both "normal" and "hard" braking data are used directly in statistical modeling process.

In both of these statistical approaches, the potential models explored were similar to those looked at in the previous CAMP FCW project (Kiefer et al, 1999), which focused on brake onset conditions. In addition, in order to potentially improve modeling results, a variety of measures were investigated which looked at "instantaneous change" in vehicle-to-vehicle kinematic conditions– or how fast vehicle-to-vehicle kinematic conditions are changing. These new approaches proved very fruitful in the logistic regression approach (discussed further below).

Both the logistic and linear regression approaches utilized the following "raw" data available at last-second braking onset: following driver (SV) speed, lead vehicle (POV) speed, following driver (SV) acceleration, lead vehicle (POV) acceleration (real-time, no delay), and the range between the following driver's vehicle and the vehicle ahead. In the modeling process, each observation was treated as independent even though each driver provided several observations. It should be noted that observations from the same driver are not likely to be independent, which violates the fundamental "lack of correlated error" assumption underlying regression techniques. However, the relative fit of models is more important for purposes here than the absolute fit of models, the latter of which would be affected by treating observations "non-independently". Indeed, the primary interest here is in capturing consistent patterns and trends and applying the models beyond the dataset. The most promising findings for each of the linear regression and logistic regression approaches will now be discussed, contrasted, and compared.

The Linear Regression – Required Deceleration Approach

Modeling efforts involving linear regression (which was used in the previous Kiefer et al. (1999) work) resulted in developing an equation nearly identical to the Required Deceleration Parameter (RDP) equation found in the previous Kiefer et al. work. This lack of change in the RDP equation provides validation for the original ("old") equation, and indicates the equation is robust and relatively unaffected by the new Constant ΔV and POV Decelerating-Long Headway Trials which were included in the expanded data set. The "old" and "new" RDP equations are shown below. These equations predict a required deceleration value at brake onset above which the driver is assumed to be in a hard-braking, alert appropriate condition. Note that each of the equations below assumes accurate, real-time knowledge of lead vehicle deceleration.

"Old" CAMP Required Deceleration Parameter Equation (from Kiefer et al. (1999))

required decel. (g) = -0.165 + 0.685(lead decel. in g's) - 0.00400(closing speed in MPH) + 0.080(if lead moving)

"New" CAMP Required Deceleration Parameter Equation

required decel. (g) = -0.164 + 0.668(lead decel. in g's) - 0.00368(closing speed in MPH) + 0.078(if lead moving)

In order to calculate braking onset ranges from the equations above, the predicted required deceleration values serve as input into kinematic equations used for calculating braking onset range. This braking onset range is added to a "delay time range" to calculate the actual warning onset range. The appropriate Case equation used to calculate the braking onset range (Case 1, Case 2, or Case 3) is based on the projected movement state of the POV at braking onset (POV moving or POV stationary), and the projected movement state of the POV when the SV barely contacts the POV (contact when POV is moving or contact when POV is stationary) under the required deceleration prediction (or assumption). The braking onset range is then calculated by inputting the predicted required deceleration value into the appropriate case equation below. In the equations below, the variables need to be expressed in common measurement units, which should be consistent with those used in calculating the delay time range and predicted required deceleration values above. Furthermore, deceleration values are represented as negative values. In the equations below, V_{SVP} and V_{POVP} represent the projected speeds of the SV and POV speed at SV braking onset, respectively. That is,

$$V_{SVP} = V_{SV} + (decel_{SV}(\text{Total Delay Time}))$$

$$V_{POVP} = V_{POV} + (decel_{POV}(\text{Total Delay Time}))$$

<u>Case 1</u>: POV Stationary →

$$\text{Braking Onset Range} = \frac{(V_{SVP})^2}{-2*(decel_{REQ})}$$

<u>Case 2</u>: POV Moving, contact when POV is moving →

$$\text{Braking Onset Range} = \frac{(V_{SVP} - V_{POVP})^2}{-2*(decel_{REQ} - decel_{POV})}$$

<u>Case 3</u>: POV Moving, contact when POV is stationary →

$$\text{Braking Onset Range} = \frac{(V_{SVP})^2}{-2*(decel_{REQ})} - \frac{(V_{POVP})^2}{-2*(decel_{POV})}$$

It should be noted again that only the "hard braking" instruction data is directly used for generating this required deceleration model. The previous CAMP FCW work (Kiefer et al., 1999) established that across a wide range of vehicle-to-vehicle kinematic conditions, the 95th percentile required deceleration values under "normal" last-second braking instructions corresponded very closely to the 50th percentile required deceleration values under "hard" last-second braking instructions (see Figure 10 for an illustration of this correspondence for one specific kinematic condition). Furthermore, 50th percentile required deceleration values under "hard" last-second braking instructions corresponded very closely to the mean values under the same braking instructions. Hence, in an indirect sense, the normal braking data are used to ensure braking onset assumptions are on the fringe of the normal braking envelope (and hence, will minimize "early" assumptions surrounding hard braking onsets). However, it should be noted that the validity of this assumption remains dependent on the aforementioned relationship (95th percentile normal = 50th percentile hard = mean hard) remaining consistent across a wide range of kinematic conditions. Fortunately, as shown in Figure 11, this relationship remains very robust across the 17 kinematic conditions not only for last-second braking, but also somewhat remarkably to a large extent for last-second steering, as shown in Figure 12 (with the largest difference occurring in the 60/60/0.39 "hard" steering condition, where there is a 17% difference between the 95th percentile "normal" steering and mean "hard" steering values). Also, note that in Figure 12, the mean "hard" last-second steering onset value for the 60/60/0.15 condition is hidden in the figure because it is identical to the corresponding 95th percentile "normal" last-second steering onset value (i.e., 0.29 g's).

The Logistic Regression – Inverse TTC-Based Approach.

Unlike the previous modeling approach, which predicts a continuous required deceleration value at brake onset, the logistic regression approach predicts the probability that a driver is in a "hard" braking onset situation (and hence, <u>not</u> in a "normal", albeit last-second, braking onset situation) for any given kinematic condition. Hence, rather than predicting a continuous dependent variable (as in linear

Figure 10. Required-Deceleration Based Approach for the Assumed Driver Deceleration Parameter

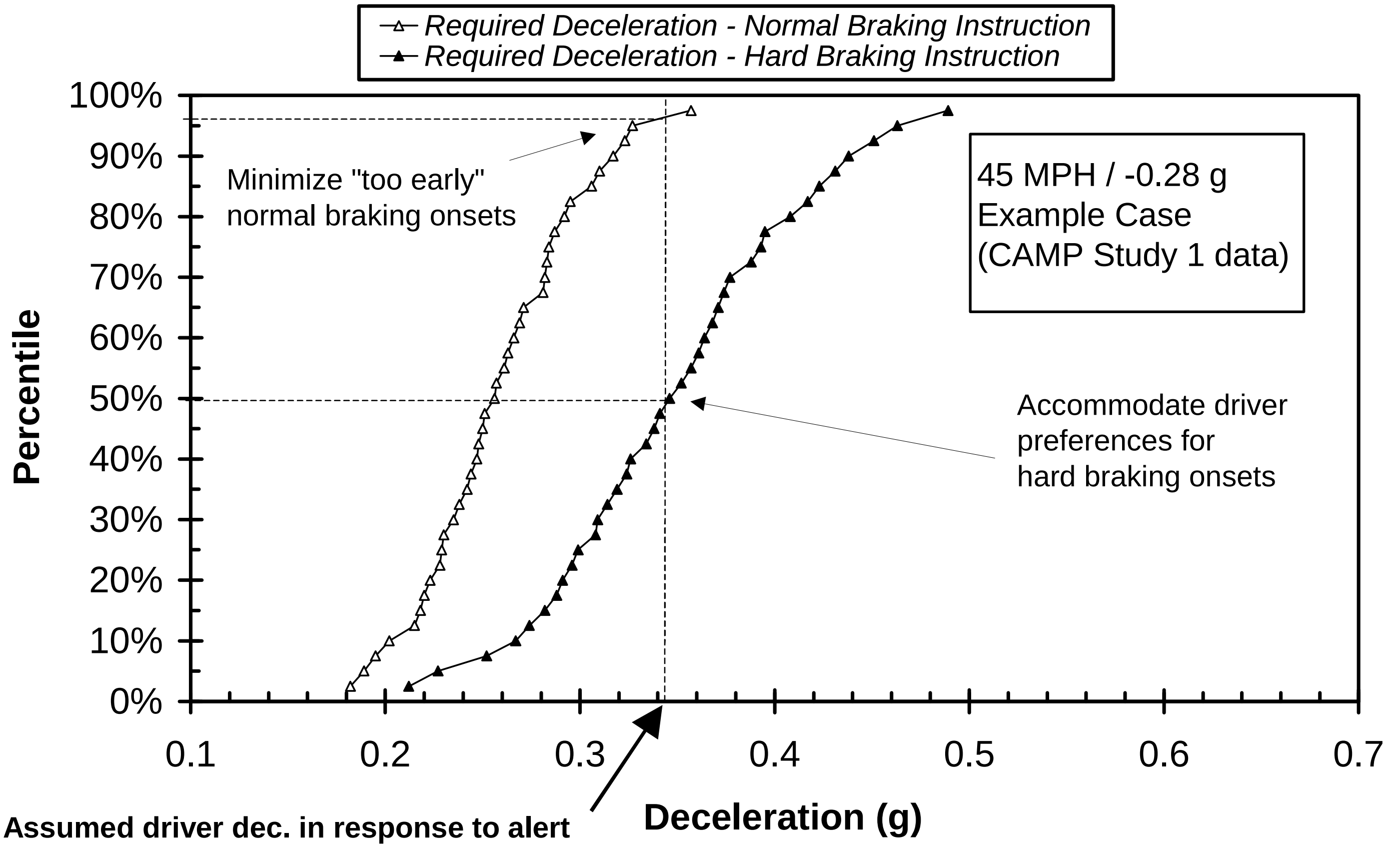
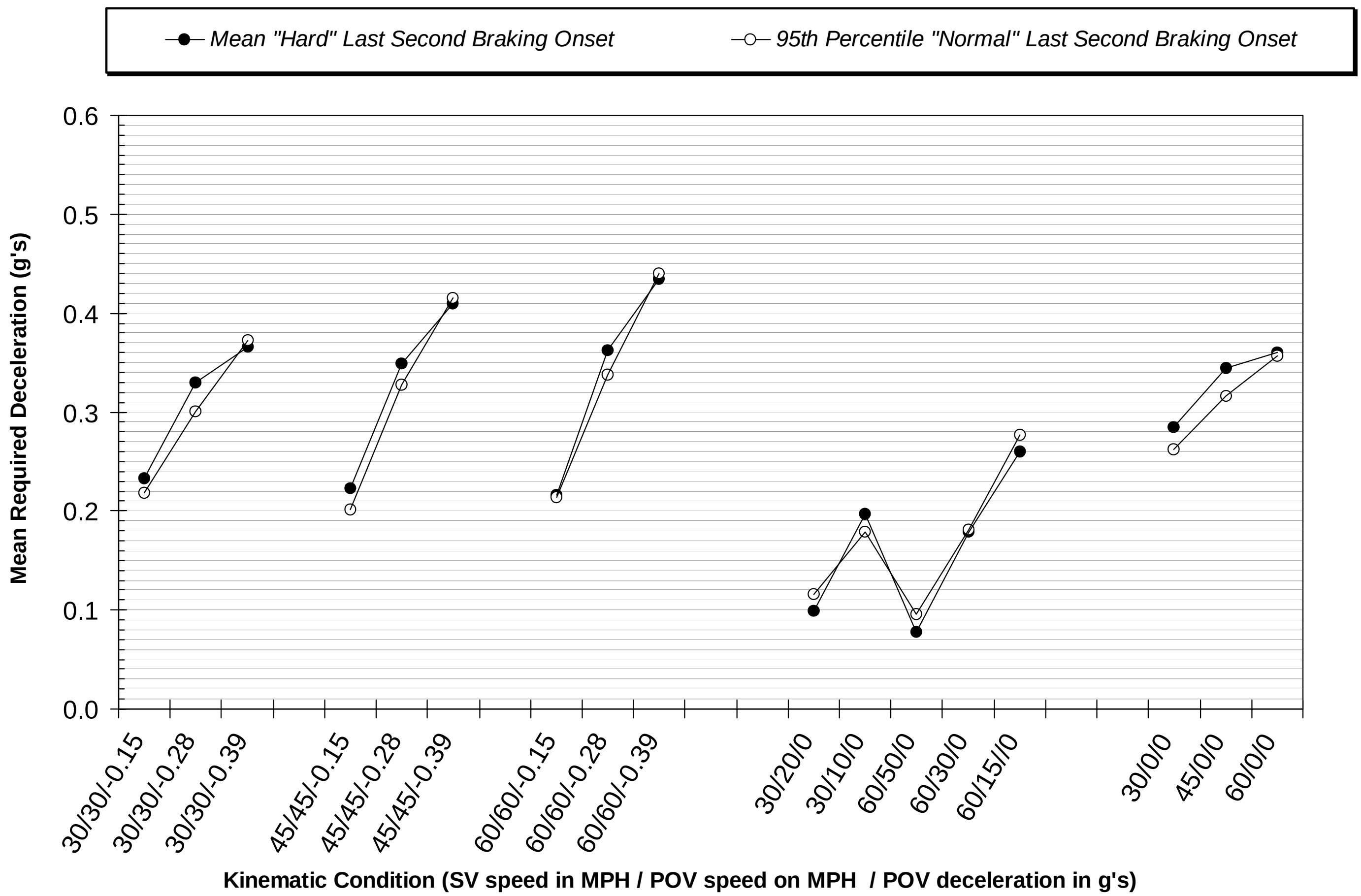
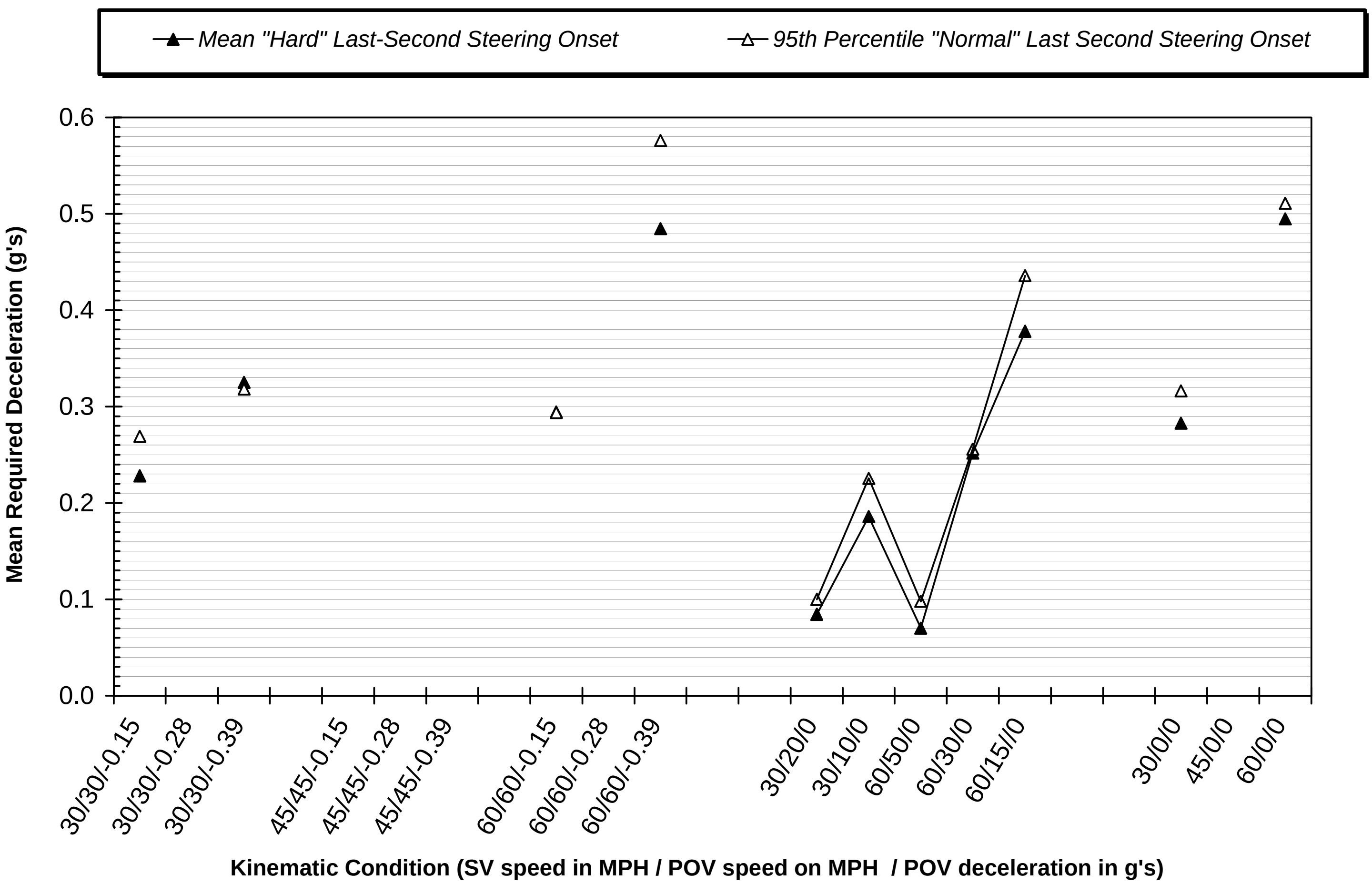


Figure 11. Mean "Hard" Required Decelerations and 95th Percentile "Normal" Required Decelerations at Last-Second Braking Onset for Each Kinematic Condition



<u>Figure 12</u>. Mean "Hard" Required Decelerations and 95th Percentile "Normal" Required Decelerations at Last-Second Steering Onset for Each Kinematic Condition



regression), the current logistic regression approach predicts a binary dependent variable (normal braking situation, hard braking situation). Furthermore, unlike the linear regression approach above which only uses data directly from the "hard" braking instruction condition, the logistic regression approach has the distinct advantage of also using data directly from the "normal" braking instruction condition.

As with the linear regression approach described above, the prediction equation resulting from this approach is used in calculating the Braking Onset Range, which along with the Delay Time Range, is used to calculate the (total) Warning Range (Kiefer et al., 1999). After a cut-off value corresponding to the probability that the driver is in a "hard" braking onset situation is selected for the logistic regression approach (e.g., probability=0.75), the prediction equation can be re-written to give the range at which a warning should be given current kinematic conditions. Whenever the observed range to the vehicle ahead is lower than the predicted warning range corresponding to the selected cut-off probability value, then the crash alert criterion is violated and the crash alert should be presented.

In this logistic regression approach, last-second "hard" braking trials are treated as a success (or "1"), and last-second "normal" braking trials are treated as a failure (or "0"). A best-fitting equation is then generated for a dimensionless variable "x" which is forced to map onto a (closed) cumulative distribution function ranging from 0 to 1. Various functions can be chosen for this cumulative distribution function. In this case, a logistic function was chosen, where:

$$p = \frac{1}{1 + e^{-x}}$$

where e is the base on the natural logarithm or 2.7182818…

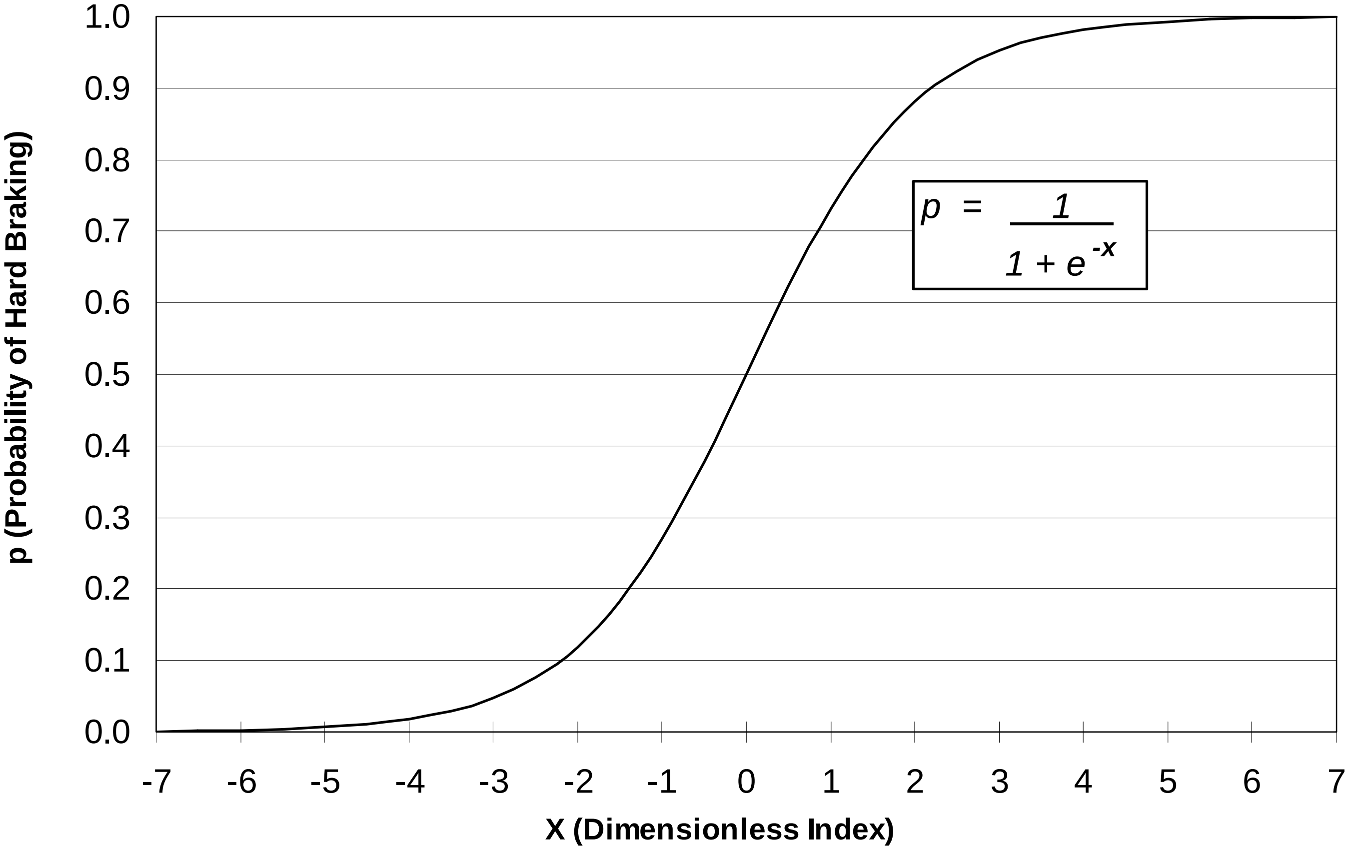
This function is shown in Figure 13. This equation can be re-expressed in the following manner when solving for x:

$$x = -\ln((1/p) - 1)$$

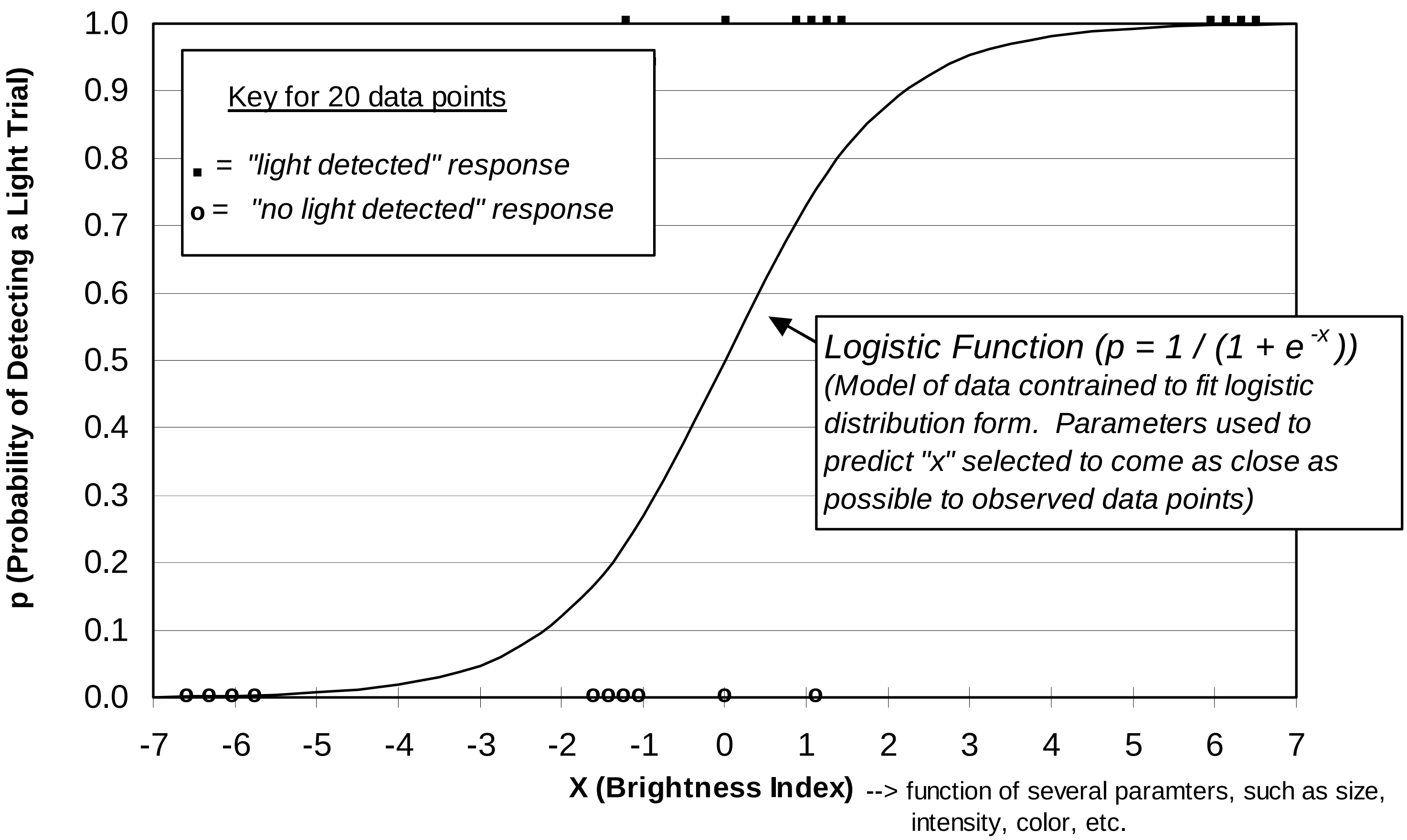
Since many readers may be unfamiliar with logistic regression techniques, a simple light-detection example is provided in Figure 14. In this example, logistic regression is used to develop a model for predicting the probability a light will be detected. Various factors could contribute to the probability a light will be detected, and for this example, let us assume the size, intensity, and color of the light were varied during 20 test trials. Furthermore, let us assume that for 10 of these trials the light was detected, and that for the remaining 10 trials the light was not detected. The data points shown in Figure 14 represent data from these 20 trials, where the 10 trials in which the light was detected are shown scattered along the horizontal line with a probability value of "1", and the 10 trials in which the light was not detected are shown scattered along the horizontal line with a probability value of "0".

The goal of logistic regression is to solve for the brightness index "x" (by using the size, intensity, and color as factors) such that the resultant function (x=function(size, intensity, color)) does the best job of mapping onto the logistic function. In Figure 14, the value of this brightness index "x" is shown on horizontal axis, and the probability the light is detected is shown on the vertical axis. Note that for low values of the brightness index (-6, -7), the logistic function in this example predicts correctly that the probability of detecting the light is 0 (or 0%). Conversely, for high values of the brightness index (6, 7),

Figure 13. Logistic Cumulative Distribution Function



<u>Figure 14</u>. Logistic Regression Example: Probablility of Detecting Light as a Function of Brightness Index "x"



the logistic function in this example predicts correctly that the probability of detecting the light is 1.0 (or 100%). For intermediate x values ranging from –2 to 2, the brightness index values do not predict light detection with 100% accuracy. Note that 2 data points resulted in a brightness index value of 0. In one case, the light was detected, and in the other case, the light was not detected. Hence, the logistic function in this example predicts correctly that the probability of detecting a light at the brightness index value of 0 is 0.5 (or 50%). Finally, note that 5 data points resulted in brightness index values ranging between 1 and 2. In 4 of these 5 cases, the light was detected, and in the remaining case, the light was not detected. Hence, the logistic function in this example predicts that the probability of detecting a light with the brightness index value of about 1.4 is roughly 0.8 (or 80%). Note that for any given value of the brightness index, a corresponding probability "p" can be generated.

Another simple logistic regression example, more directly related to predicting hard braking onsets, is shown in Figure 15. In this case, the probability of detecting a light in the previous example is substituted by the probability of a hard braking onset scenario, "x" (the braking index) is now a function of various kinematic parameters (such as vehicle speeds and accelerations, and the range between the two vehicles), and the data points shown now represent "hard" braking trials (indicated with a probability value of "1") and "normal" braking trials (indicated with a probability value of "0") for various index values.

Note that for any given value of the braking index, the corresponding probability that the existing kinematic conditions are a "hard braking onset scenario" can be determined. Hence, with this approach, the designer can apriori select a probability value (e.g., p=0.75) of hard braking onset, which then can be compared to the observed p value the driver is currently experiencing. If the observed p value (e.g., 0.85) is higher than the value chosen apriori by the designer, the conditions are "alert appropriate" from a braking onset perspective. Note that in the current data set consisting of both last-second "normal" and last-second "hard" braking trials, choosing a p=0.75 value corresponds loosely to choosing a p=0.50 value for the last-second "hard" braking data set only. This is mentioned here because a p=0.75 value was shown to be the most promising for the model discussed below. More generally, the p-value can be potentially varied to address driver variables (e.g., gender, age) and various weather/environmental conditions. In addition, the p-value could potentially be used to provide rationale for graded alerts, for different alert timing settings, and for changing false alarm/miss trade-offs based on kinematic conditions (e.g., during suspected lane-change scenarios). With respect to this latter point, Figure 16 and Figure 17 represent the effects varying p from 0.50 to 0.75 have on predicted "early" and "late" brake onsets (which are discussed later). Note that as p increased from 0.50 to 0.75, the number of "early" brake onsets decrease, and the number of "late" brake onsets increase.

Hopefully, the reader by now has developed at least a conceptual understanding of the logistic regression approach. The discussion below focuses on discussing the functions solving for the braking index "x" that best mapped onto the logistic function described above, using data from both the last-second "normal" and last-second "hard" braking trials.

<u>Figure 15</u>. Logistic Regression Example: Probablility of "Hard Braking" Scenario as a Function of Braking Index "x"

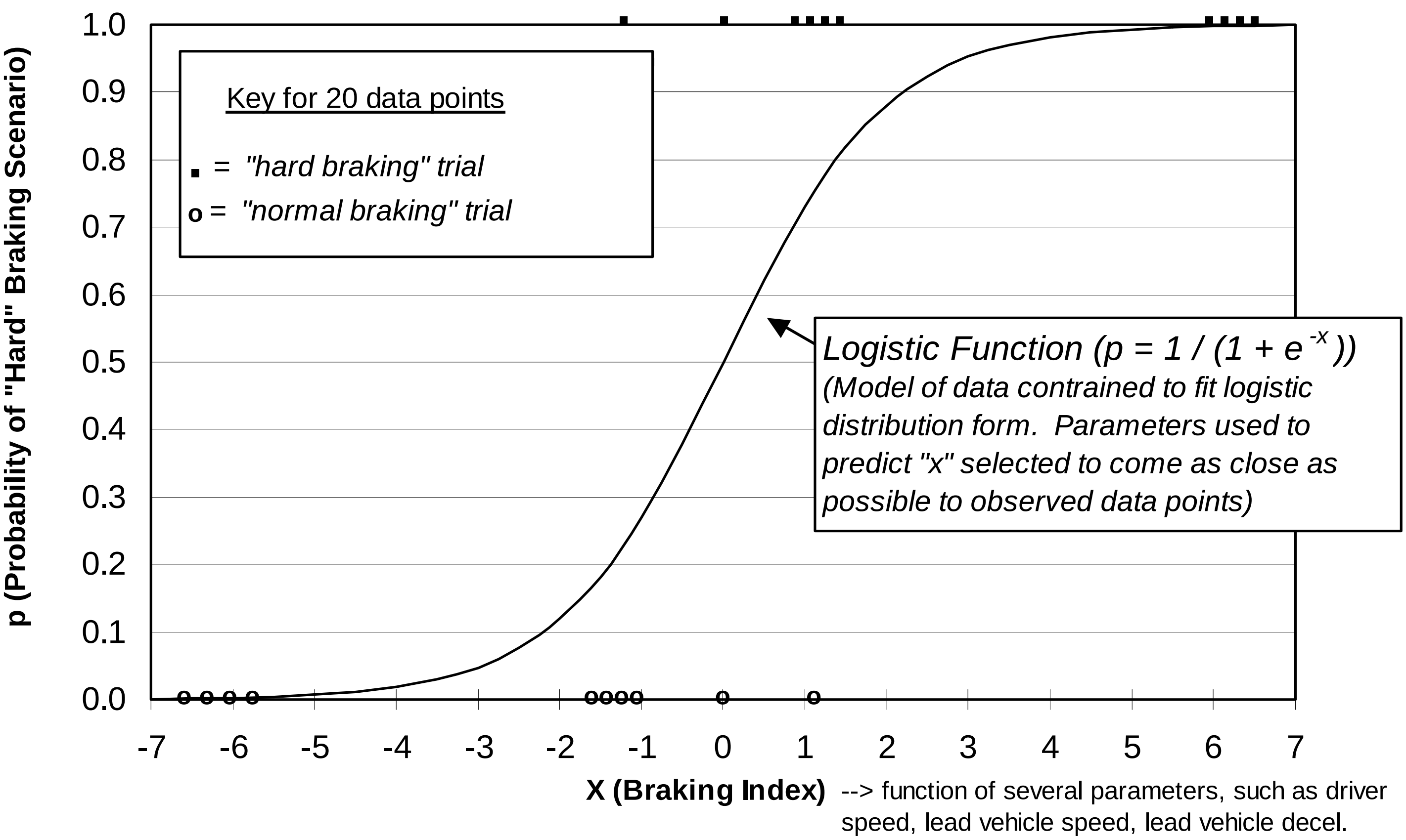
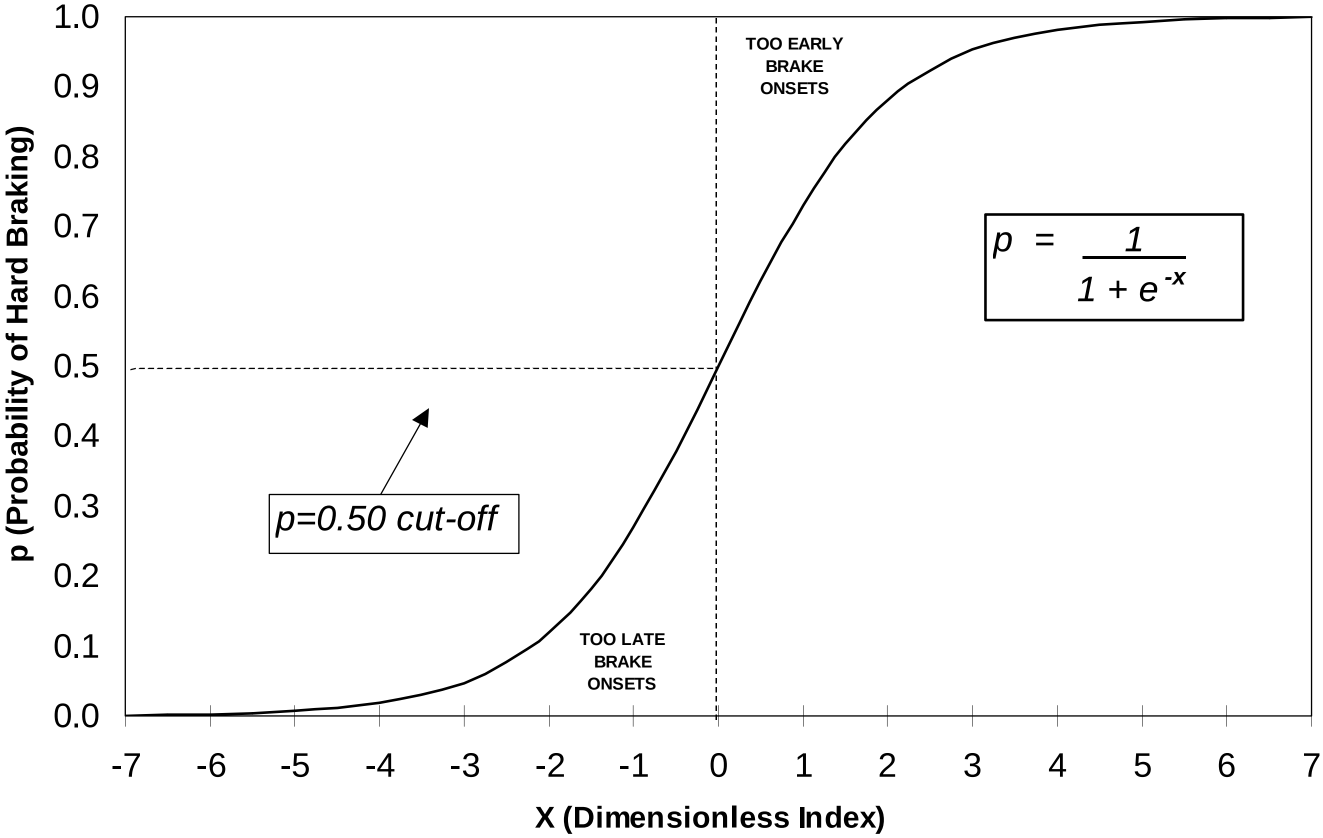
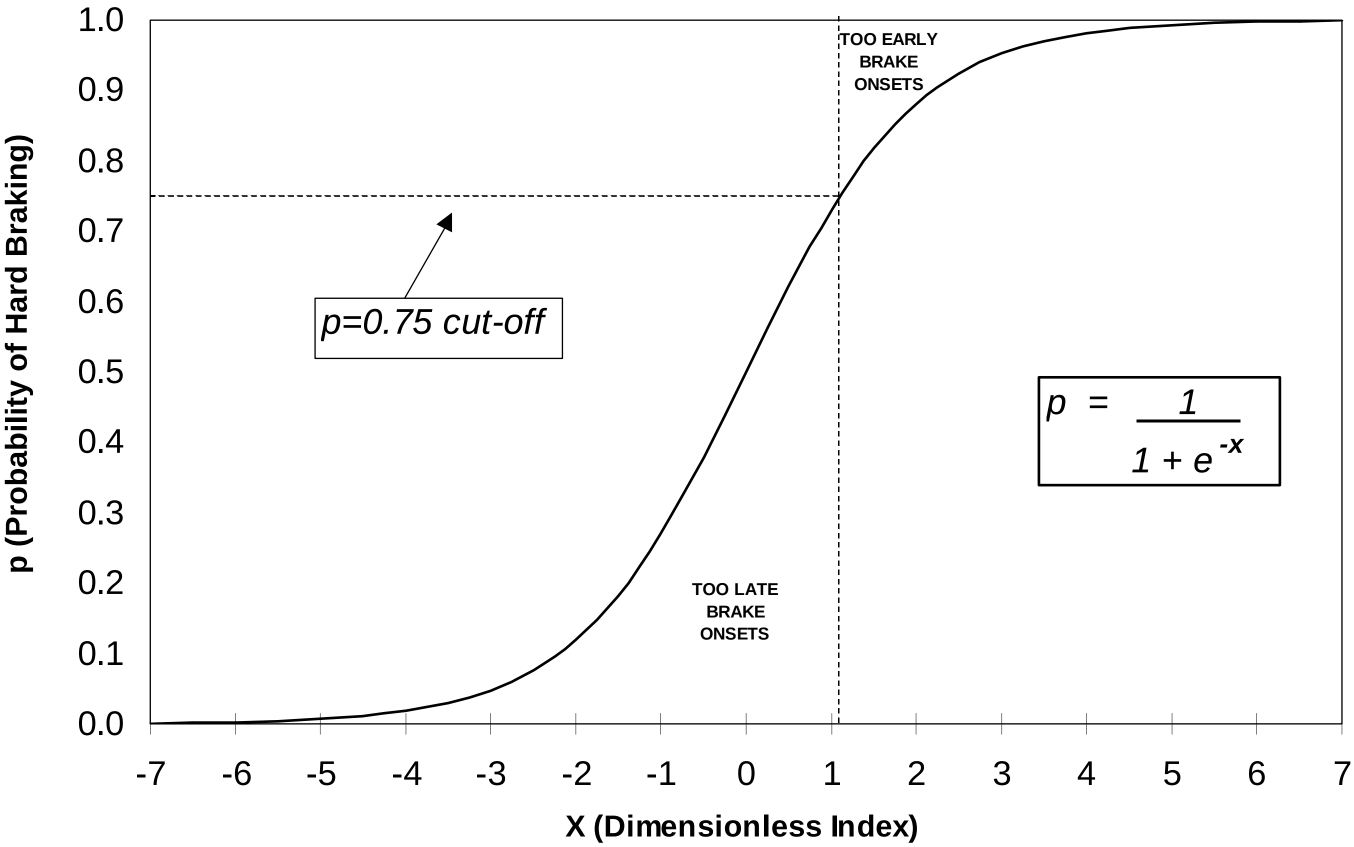


Figure 16. **Logistic Cumulative Distribution Function with p=0.50 Cut-Off**



<u>Figure 17</u>. Logistic Cumulative Distribution Function with p=0.75 Cut-Off



As was mentioned above, in addition to the modeling approaches explored in the previous CAMP FCW work (Kiefer et al., 1999), efforts here explored measures which looked at the "instantaneous change" in vehicle-to-vehicle kinematic conditions (in terms of time derivatives), or how fast vehicle-to-vehicle kinematic conditions are changing per unit time. Below are the time derivatives of some basic kinematic quantities of a subject vehicle (SV) approaching another principal other vehicle (POV).

Quantity	Variable	Time derivative, i.e., $\frac{d}{dt}(\text{Variable})$
Range		$-\Delta V = V_{POV} - V_{SV}$
Closing speed	$\Delta V = V_{SV} - V_{POV}$	$\Delta a = a_{SV} - a_{POV}$
Time-To-Collision or TTC (assuming both vehicles maintain current speed)	$TTC = \frac{R}{\Delta V}$	$-1 - TTC \cdot \frac{\Delta a}{\Delta V}$
Required deceleration to avoid impact, assuming constant accelerations of both vehicles	$a_r = a_{POV} + \frac{\Delta V^2}{-2R}$, when $R \le \frac{\Delta V \cdot V_{POV}}{-2a_{POV}}$	$\frac{d}{dt}(a_r) = \frac{-\Delta V}{R}\left(\Delta a + \frac{\Delta V^2}{2R}\right) = \frac{1}{TTC} \cdot (a_r - a_{SV})$
Required deceleration to avoid impact, assuming constant acceleration of both vehicles	$a_r = \frac{-V_{SV}^2}{2\left(R + \frac{V_{POV}^2}{-2a_{POV}}\right)}$, when $R > \frac{\Delta V \cdot V_{POV}}{-2a_{POV}}$	$\frac{d}{dt}(a_r) = \frac{2}{V_{SV}} \cdot a_r(a_{SV} - a_r)$

This effort included exploring the time derivative of required deceleration (i.e., how fast required deceleration is changing per unit time). During the process of exploring this measure, it was noticed that the inverse TTC-Case 1 measure (or $\Delta\ Velocity / Range$) appeared in the time derivative of required deceleration for 2 of the 3 kinematic cases described in "The Linear Regression – Required Deceleration Approach" section above (namely, Case 1 and Case 2), which are shown (collectively) as the fourth quantity in the table above. This quantity indicates that the fractional change in required deceleration per unit time (i.e., d/dt(a_r) divided by a_r itself) equals 1/TTC.

Ultimately, the inverse TTC-Case 1 measure turned out to be the single most important predictor during the logistic regression efforts. For the sake of brevity, this approach will be subsequently referred to as the "*Inverse TTC*" (rather than the "Inverse TTC-Case 1") based approach.

The following discussion describes solutions for "x" which did the best job of mapping onto the logistic function using the "normal" and "hard" last-second braking data. Both "*2-Tiered*" and "*3-Tiered*" Inverse TTC based approaches were developed.

For the 2-Tiered Inverse TTC approach, similar to the Required Deceleration approach described above, two separate equations were developed for lead vehicle moving and lead vehicle stationary cases, respectively. The resulting equations for the 2-Tiered approach are shown below:

If lead vehicle moving: $x = -5.384 + 15.600(\Delta\ Velocity / Range) + 0.0468(driver\ speed\ in\ MPH)$

If lead vehicle stationary: $x = -8.585 + 23.559(\Delta\ Velocity / Range) + 0.0468(driver\ speed\ in\ MPH)$

Note that in comparing these two equations, different intercepts and slopes of the Inverse TTC component are required, whereas the speed component remains constant. Also note that unlike with the Required Deceleration approach, which requires accurate lead vehicle deceleration information, the assumption here is merely that the FCW system can distinguish between vehicles that are moving (i.e., POV Decelerating Trials and Constant ΔV Trials in this context) versus stationary (i.e., POV Stationary Trials in this context). This is a potential advantage of this approach over the Required Deceleration approach given current technological challenges and limitations in sensing lead vehicle deceleration in a timely and accurate fashion.

For the 3-Tiered Inverse TTC approach, three separate equations were developed for lead vehicle moving and braking, lead vehicle moving and <u>not</u> braking, and lead vehicle stationary cases. These correspond to POV Decelerating Trials, Constant ΔV Trials, and POV Stationary Trials, respectively, in this context. The resulting equations for the 3-Tiered approach are shown below:

If lead vehicle moving-braking: $x = -6.092 + 18.816(\Delta Velocity / Range) + 0.0534(driver\ speed\ in\ MPH)$

If lead vehicle moving-not braking: $x = -6.092 + 12.584(\Delta Velocity / Range) + 0.0534(driver\ speed\ in\ MPH)$

If lead vehicle stationary: $x = -9.073 + 24.225(\Delta Velocity / Range) + 0.0534(driver\ speed\ in\ MPH)$

Note that in comparing these three equations, as with the 2-Tiered approach, different slopes for the inverse TTC component are required, whereas the speed component remains constant. Once again, note the assumption for this 3-Tiered approach is that the FCW system can distinguish between vehicles that are moving and braking, moving and not braking, and stationary. Again, accurate knowledge of lead vehicle deceleration (as in the Required Deceleration approach) is not required. Overall, as one might expect, the 3-Tiered Inverse TTC approach yielded more promising results than the 2-Tiered Inverse TTC based approach, and hence, the 2-Tiered approach will not be discussed any further. Furthermore, as was mentioned above, a p=0.75 value appears to be a promising parameter to assume for the 3-Tiered approach. As will be discussed shortly, such a value resulted in maintaining overall "early" and overall "late" brake onset prediction rates fewer than 5%. Furthermore, it should be noted that this 3-Tiered Inverse TTC model can be elegantly described as a model that assumes the driver deceleration response (in response to the crash alert) is based on an inverse TTC threshold that decreases linearly with speed.

In order to calculate braking onset ranges (in feet), the following general equation is used:

$$\text{Braking Onset Range} = \frac{b(V_{SV} - V_{POV})}{(\ln((1/p^*) - 1)\text{-}a) - c(V_{SV})}$$

The following are assumed for *a, b,* and *c* (which are taken from the equations shown above):

If lead vehicle moving and braking,
a= 6.092
b= -18.816
c= -0.0534

If lead vehicle moving and not braking,
a= 6.092
b= -12.584
c= -0.0534

If lead vehicle stationary,
a= 9.073
b= -24.225
c= -0.0534

It should be noted that in the actual implementation of this Inverse TTC-based approach in a crash alert timing algorithm, modifications would be needed to avoid discontinuities in response to transitions between the various cases described above (e.g., the transition from lead vehicle stationary to lead vehicle moving cases). Pseudo-code for the actual implementation of the 3-Tiered Inverse TTC Model can be found in Appendix E.

Comparing the Required Deceleration Model and the 3-Tiered Inverse TTC Model

The braking onset predictions for the New Required Deceleration Model and the 3-Tiered Inverse TTC Model (p=0.75) described above were compared using the following five criteria:

(1) Predictions under "nominal" vehicle-to-vehicle kinematic conditions
(2) Residual values (i.e., differences between observed and predicted model values)
(3) Percent "early" brake onset predictions
(4) Percent "late" brake onset predictions
(5) Domain of validity considerations (i.e., the extent to which the model behaves "sensibly" across a wide range of vehicle-to-vehicle kinematic conditions, including those beyond the scope of conditions examined here)

Each of these criteria measures used for comparing models will now be discussed in turn.

Predictions under "Nominal" Vehicle-to-Vehicle Kinematic Conditions

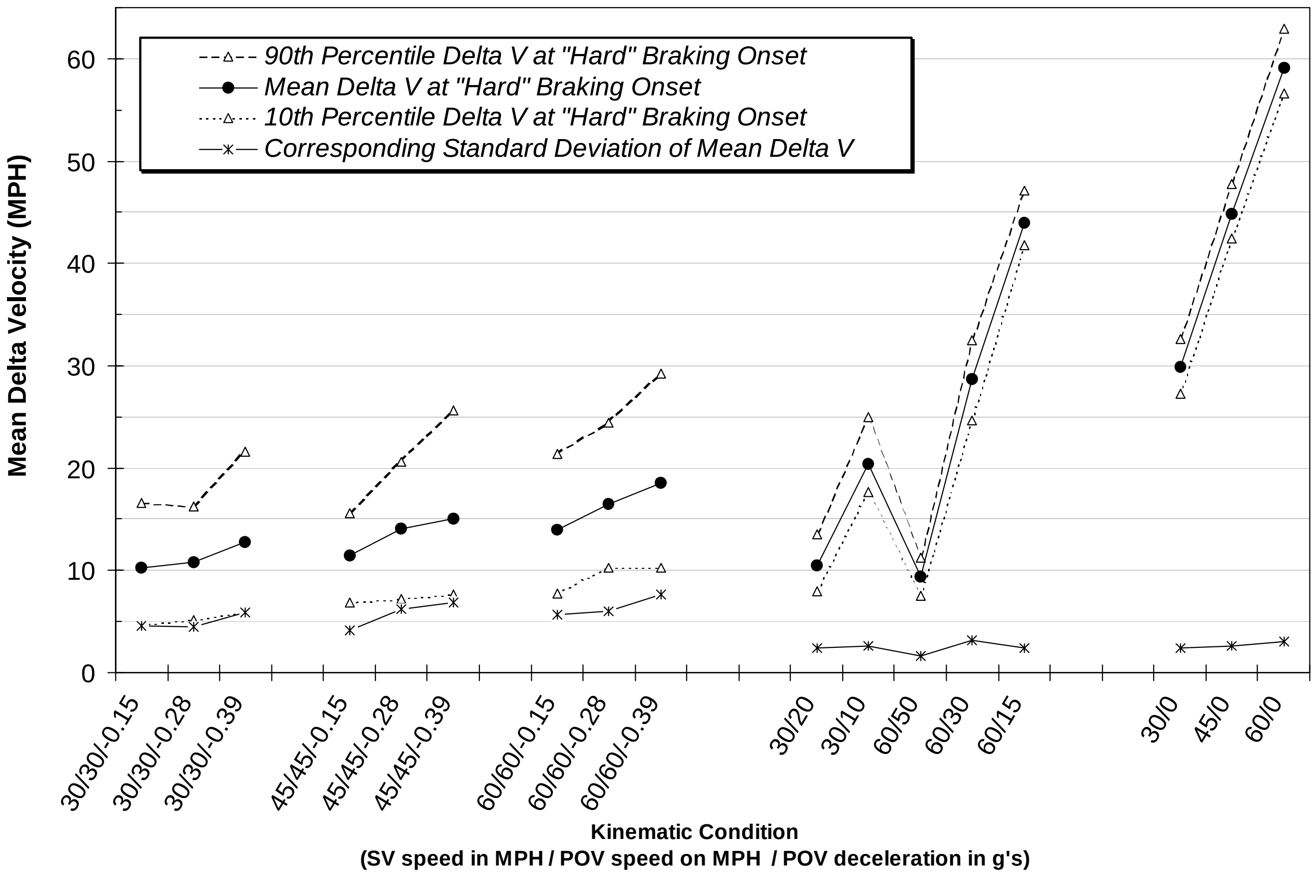
In order to compare these two models, "nominal" conditions, shown in Table 3, were identified. These "nominal" conditions were generated for each of the 17 kinematic conditions by assuming the instructed SV speeds and programmed POV decelerations, a SV acceleration value of 0, as well as the measured average POV speed at SV brake onset. In addition, Figure 18 provides the mean ΔV at "hard" braking onset across kinematic conditions, corresponding standard deviations to these values, and 10^{th} and 90^{th} percentiles for ΔV at "hard" braking onset.

Given these assumed SV speed, SV acceleration, POV speed, and POV acceleration values, ("crash alert appropriate") hard braking onset predictions were generated for each Model. (In the "Domain of Validity Considerations" section below, predictions are provided for a much larger range of

Table 3. **Definitions of the 17 "Nominal" Kinematic Conditions**

Definitions of 17 "Nominal" Kinematic Conditions Used For Model Comparisons					
Kinematic Condition (V_{SV} / V_{POV} / DEC_{POV})	SV Speed (in MPH)	POV Speed (in MPH)	Delta Velocity (in MPH)	POV Deceleration (in g's)	
30 / 30 / 0.15	30	19.8	10.2	0.15	Both Vehicles Moving at Similar Speeds, Lead Vehicle Brakes with a Constant Deceleration Profile
30 / 30 / 0.28	30	19.2	10.8	0.28	
30 / 30 / 0.39	30	17.2	12.8	0.39	
45 / 45 / 0.15	45	33.5	11.5	0.15	
45 / 45 / 0.28	45	30.9	14.1	0.28	
45 / 45 / 0.39	45	29.9	15.1	0.39	
60 / 60 / 0.15	60	46.0	14.0	0.15	
60 / 60 / 0.28	60	43.5	16.5	0.28	
60 / 60 / 0.39	60	41.5	18.5	0.39	
30 / 20	30	19.5	10.5	0	Both Vehicles Moving at Constant Speed, Lead Vehicle Moving at Lower Speed
30 / 10	30	9.6	20.4	0	
60 / 50	60	50.6	9.4	0	
60 / 30	60	31.3	28.7	0	
60 /15	60	15.6	44.4	0	
30 / 0	30	0	29.9	0	Driver Approaches Stationary Lead Vehicle
45 / 0	45	0	44.8	0	
60 / 0	60	0	59.1	0	

<u>Figure 18</u>. Mean Delta Velocities (as well as corresponding standard deviations) and 10th and 90th Delta Velocity Percentiles at "Hard" Braking Onset Across the 17 Kinematic Conditions



vehicle-to-vehicle kinematic conditions, however, corresponding observed data for these cases are not available for model comparison purposes.)

Model predictions were calculated using the required deceleration, inverse TTC-Case 2, and range measures. These measures are employed since they provide the most direct measures of actual crash risk because they employ the measured (real-time) lead vehicle deceleration values. For comparison purposes, the observed mean "hard" last-second braking and "hard" steering onsets are shown in Figure 19, which provide a benchmark from which to compare the extent to which the model results match observed values. However, strictly speaking, it should be noted that these observed values come from a wide range of initial vehicle-to-vehicle kinematic conditions, whereas the model predictions come from one specific nominal condition.

With respect to the comparison of model predictions using the required deceleration measure shown in Figure 19, the results indicated the following. Overall, it appears the 3-Tiered Inverse TTC Model performs very comparably to the New Required Deceleration Model, despite the fact that the latter model uses a much higher level of lead vehicle deceleration information. For the POV Decelerating Trials and POV Stationary Trials, these models provide very similar braking onset predictions. The biggest difference between the models occurs for Constant ΔV Trials. For these trials, the 3-Tiered Inverse TTC Model appears, overall, to match the pattern of observed "hard" braking onsets better than the New Required Deceleration Model (with the exception of the 60/15/0 condition). In addition, it appears the 3-Tiered Inverse TTC Model may perform slightly better in terms of accommodating last-second lane changes (i.e., minimizing alerts during intentional lane changes), since predictions associated with this model are generally slightly more aggressive than those associated with the New Required Deceleration Model across kinematic conditions.

The same general pattern of results can be observed in comparing these models using the TTC-Case 2 measure, which is shown in Figure 20. For reference purposes, model predictions are also shown in terms of range values (shown in Figure 21), which may provide a more intuitive measure but it should be kept in mind that this measure does not directly reflect kinematic "risk" as well as the required deceleration and TTC-Case 2 measures.

<u>Residual Values</u>

Residual values for each braking onset model were calculated by subtracting the predicted value from the observed value. For each model, a positive mean residual indicates the observed value was higher (or occurred earlier) than the predicted hard braking onset value. This positive mean residual suggests the braking onset model was on average, "too aggressive" (i.e., the prediction was on average "late"). Conversely, a negative mean residual indicates the observed value was lower (or occurred later) than the predicted hard braking onset value. This negative mean residual suggests the braking onset model was on average, "too conservative" (i.e., the prediction was on average "early"). Residuals were calculated in terms of the required deceleration, TTC-Case 2, and range measures. Overall, across these three measures, the 3-Tiered Inverse TTC Model performed very comparably to that of the New Required Deceleration Model.

The mean residuals expressed in terms of required deceleration values for each model are shown in Figure 22 across the 17 kinematic conditions. These residuals indicate, once again, that performance of the 3-Tiered Inverse TTC Model was very comparable to that of the New Required Deceleration Model, with 0.06 g's being the largest mean required deceleration residual difference across the 17 kinematic conditions.

Figure 19. Required Deceleration at Braking Onset Predictions under Nominal Conditions for Various Models (as well as Mean "Hard" Required Decelerations at Last-Second Braking/Steering Onset) for Each Kinematic Condition

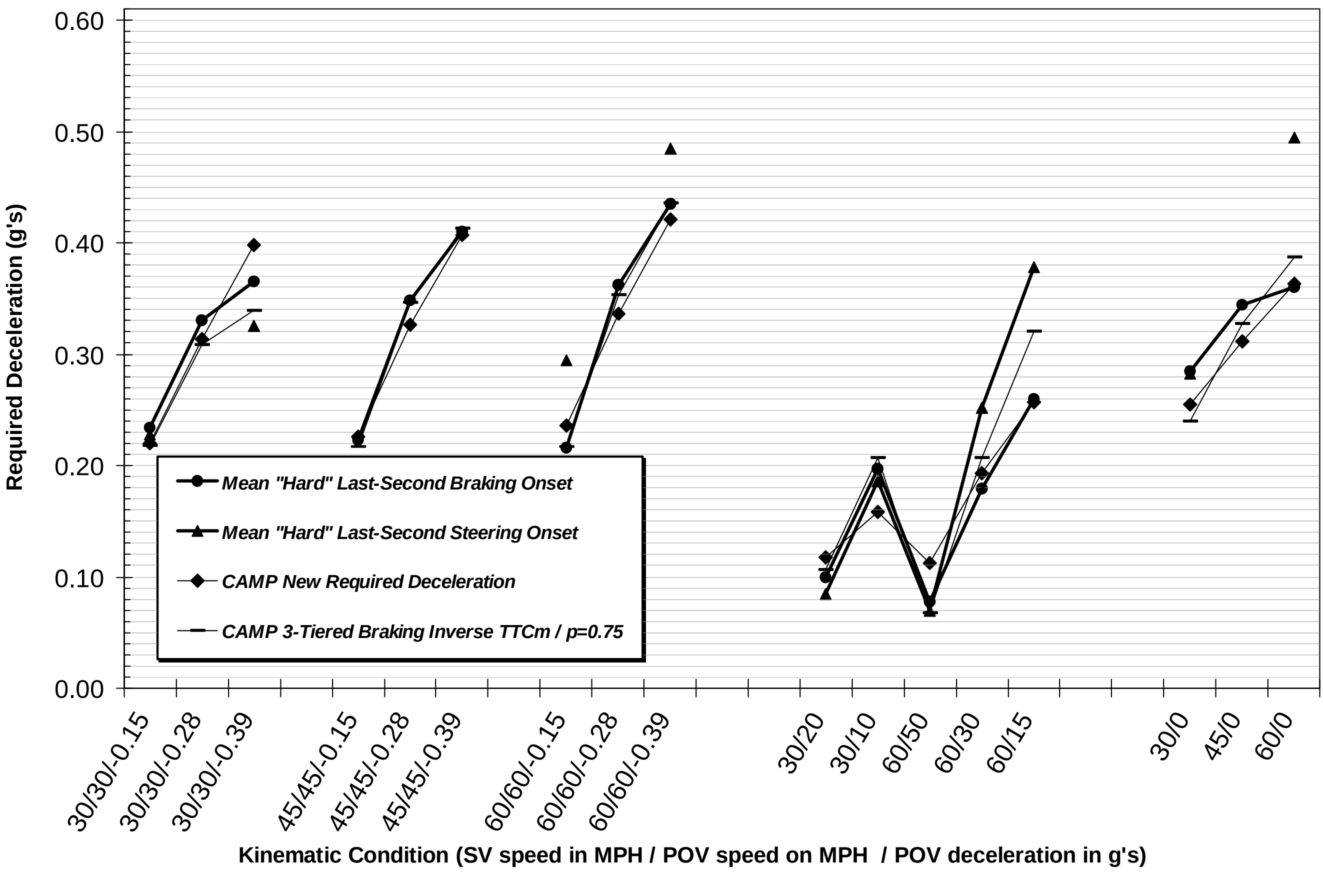


Figure 20. TTC-Case 2 at Braking Onset Predictions under Nominal Conditions for Various Models (as well as Mean "Hard" TTC-Case 2 at Last-Second Braking/Steering Onset) for Each Kinematic Condition

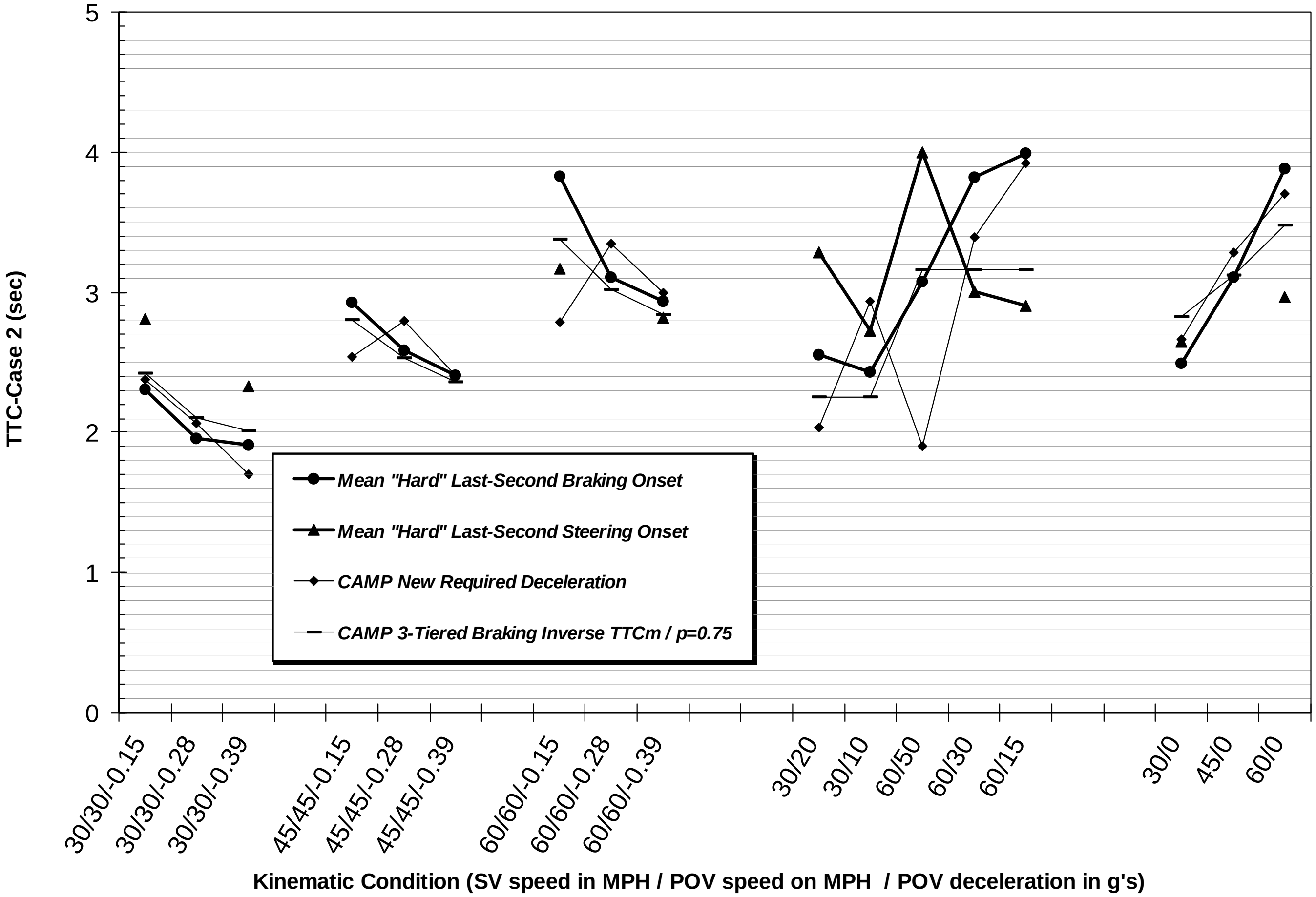
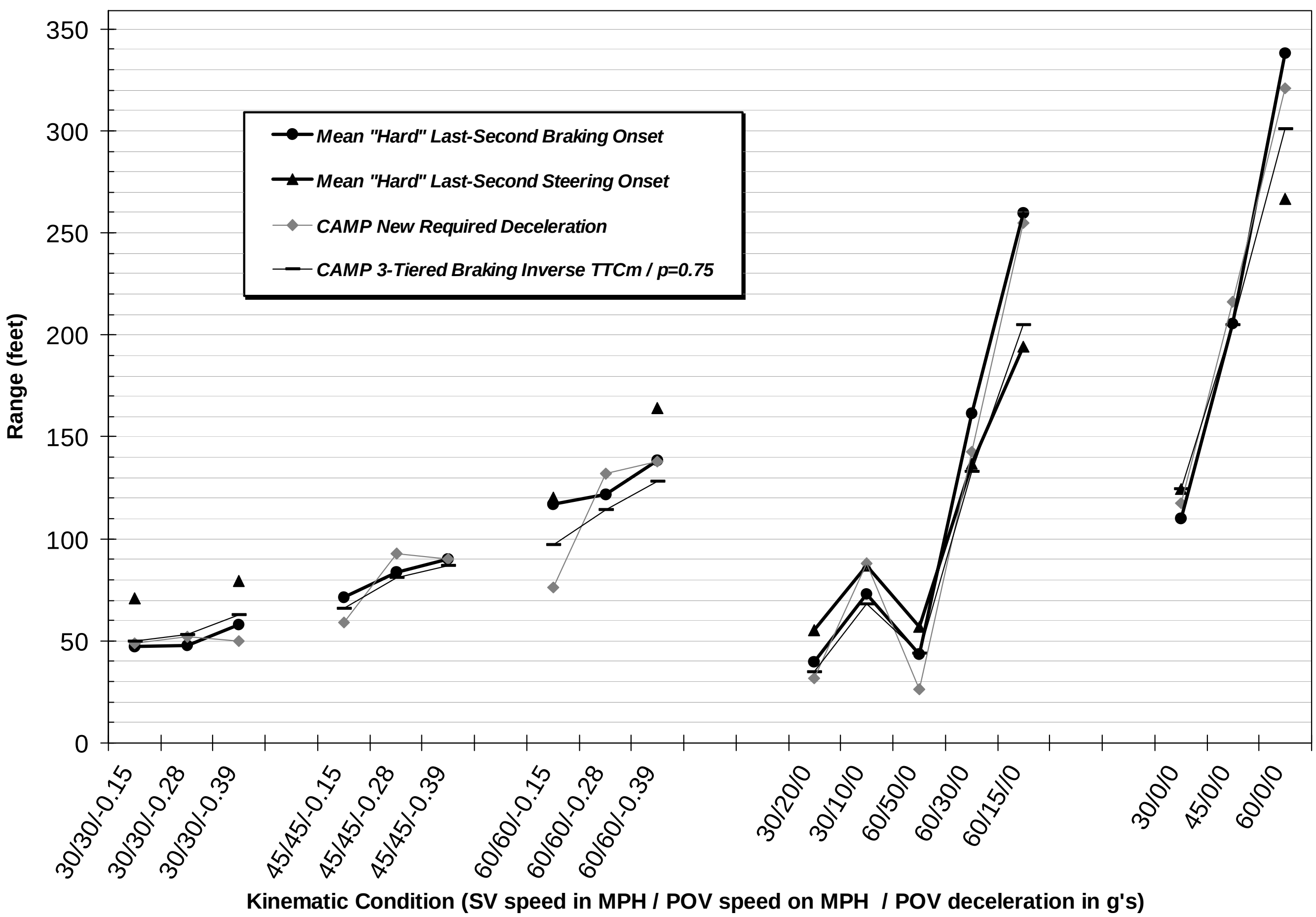
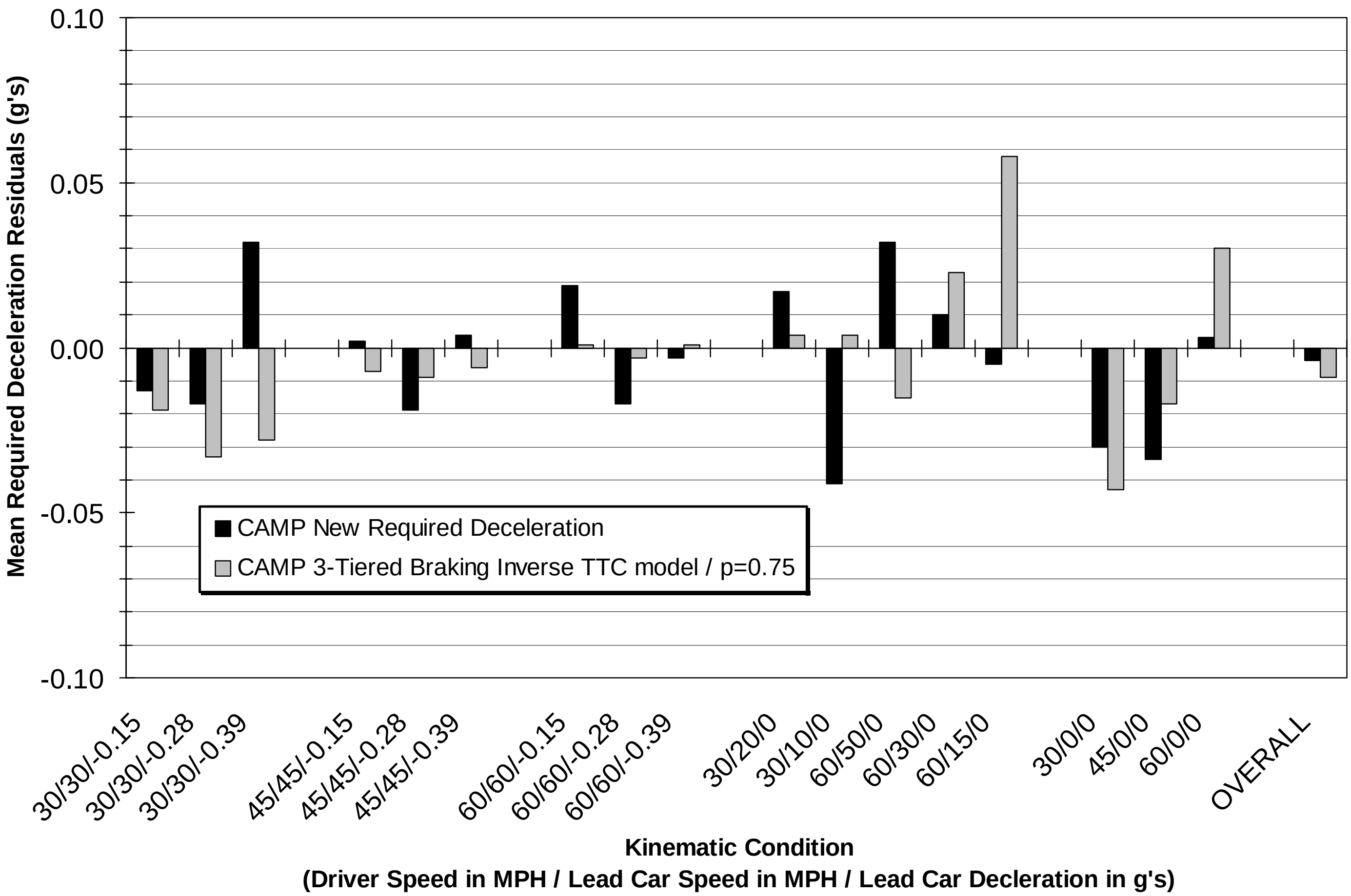


Figure 21. Range at Braking Onset Predictions under Nomimal Conditions for Various Models (as well as Mean "Hard" Range at Last-Second Braking/Steering Onset) for Each Kinematic Condition



<u>Figure 22</u>. Mean Required Deceleration Residuals (Observed - Predicted Values) for Brake Onset for Each Model Across Kinematic Conditions



Overall, the mean required deceleration residuals for the 3-Tiered Inverse TTC Model and the New Required Deceleration Model range from –0.4 to + 0.6 and –0.4 to + 0.6, respectively, across the 17 kinematic conditions.

The mean residuals expressed in terms of TTC-Case 2 values for each model are shown in Figure 23 across the 17 kinematic conditions. Once again, the performance of the 3-Tiered Inverse TTC Model was very comparable to that of the New Required Deceleration Model. Overall, the mean TTC-Case 2 residuals for the 3-Tiered Inverse TTC Model and the New Required Deceleration Model range from -0.3 to +0.9 and -0.4 to + 1.2, respectively, across the 17 kinematic conditions.

For reference purposes, mean range residual values are provided in Figure 24, which once again, may provide a more intuitive feel for the reader of the magnitude of the differences observed in predictions across models, but do not as directly reflect kinematic "risk" relative to the required deceleration and TTC-Case 2 measures. Results from the mean range residuals for the New Required Deceleration Model are remarkable stable, with only one kinematic condition exceeding 20 feet (slightly larger than 1 mid-size car length).

Percent "Early" Brake Onset Predictions

Another opportunity to make relative comparisons across these two models is to examine whether the predicted hard braking onset ranges are "early". In this analysis, an "early" predicted "hard" braking onset range is defined to occur when the predicted "hard" braking onset range is larger than the observed *"normal" (last-second) braking onset* range for a given trial. It should be noted that these results need to be considered jointly with the "late" brake onset prediction described below (i.e., lower "early" rates will generally result in higher "late" rates, and conversely, higher "early" rates will generally result in lower "late" rates).

The results for each model are shown in Figure 25. Results indicated that the "early" rates appear more stable across kinematic conditions with the 3-Tiered Inverse TTC Model relative to the Required Deceleration Model, and there is a slightly lower overall "early" rate with the 3-Tiered Inverse TTC Model (4.4% versus 6.9% "early" rates).

For exploratory purposes, a second "early" criterion was evaluated in an attempt to address the extent to which a braking onset model based on braking data could be negatively impacted by intentional lane-change maneuvers. An "early" predicted "hard" braking onset range is defined to occur when the predicted "hard" braking onset range is larger than the observed *"normal" (last-second) steering onset* range for a given trial. The results for this "early" criterion are shown in Figure 26. Overall, results indicated once again a slightly lower overall "early" rate with the 3-Tiered Inverse TTC Model than the New Required Deceleration Model (15.7% versus 17.2% "early" rates). More generally, as was suggested by earlier results, the magnitude of these "early" brake onset rates tends to increase as ΔV at braking onset increases, and is quite high in the high ΔV conditions.

Percent "Late" Brake Onset Predictions

Unfortunately, this measure is inherently less straightforward than calculating "early" rates, given potential differences between last-second "hard" braking behavior observed under experimental conditions and actual driver braking capabilities. Hence, two different criteria, a fixed criterion and a variable criterion (based on driver speed) were considered which varied in terms of driver braking assumptions.

Figure 23. Mean TTC-Case 2 Residuals (Observed - Predicted Values) for Brake Onset for Each Model Across Kinematic Conditions

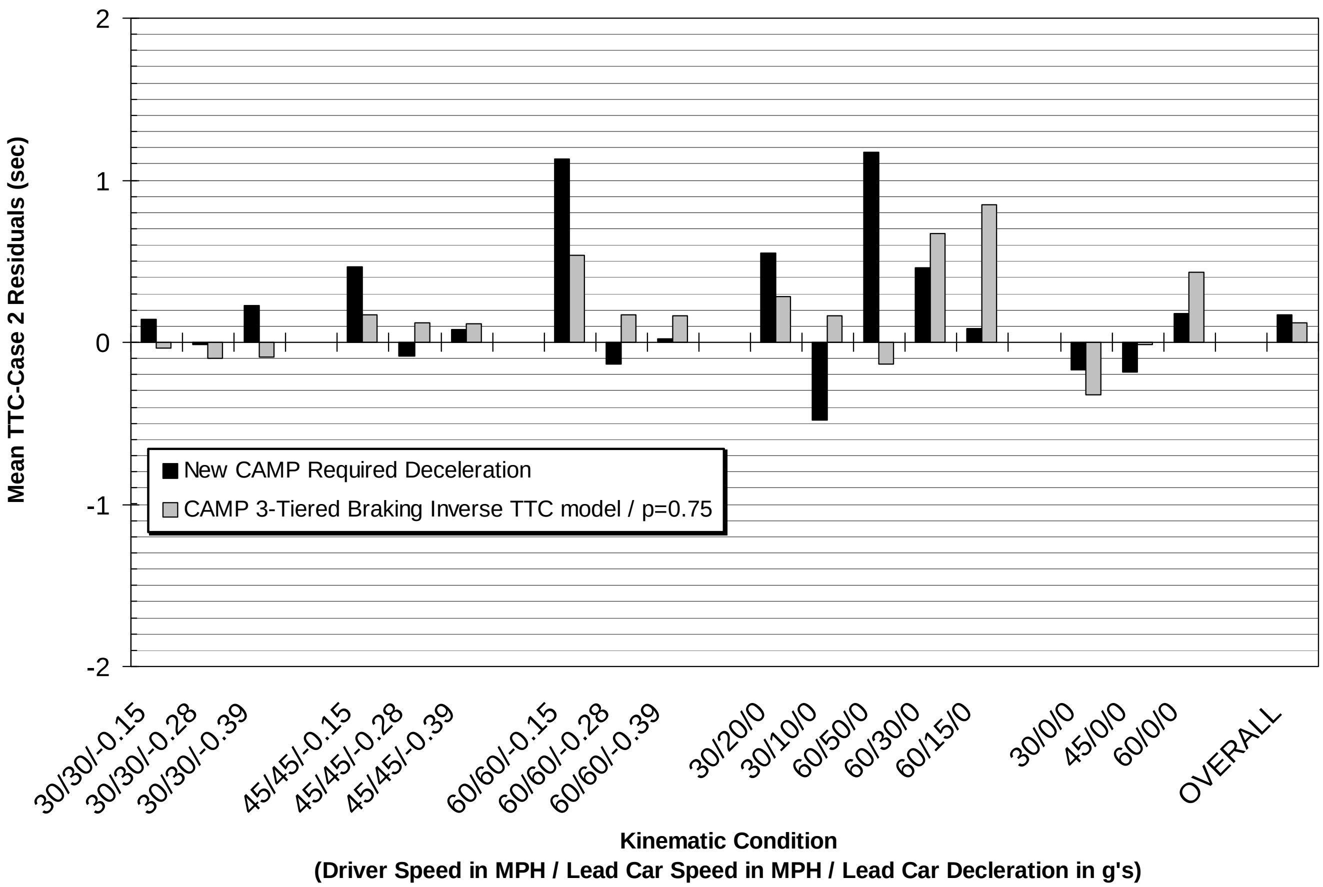


Figure 24. Mean Range Residuals (Observed - Predicted Values) for Brake Onset for Each Model Across Kinematic Conditions

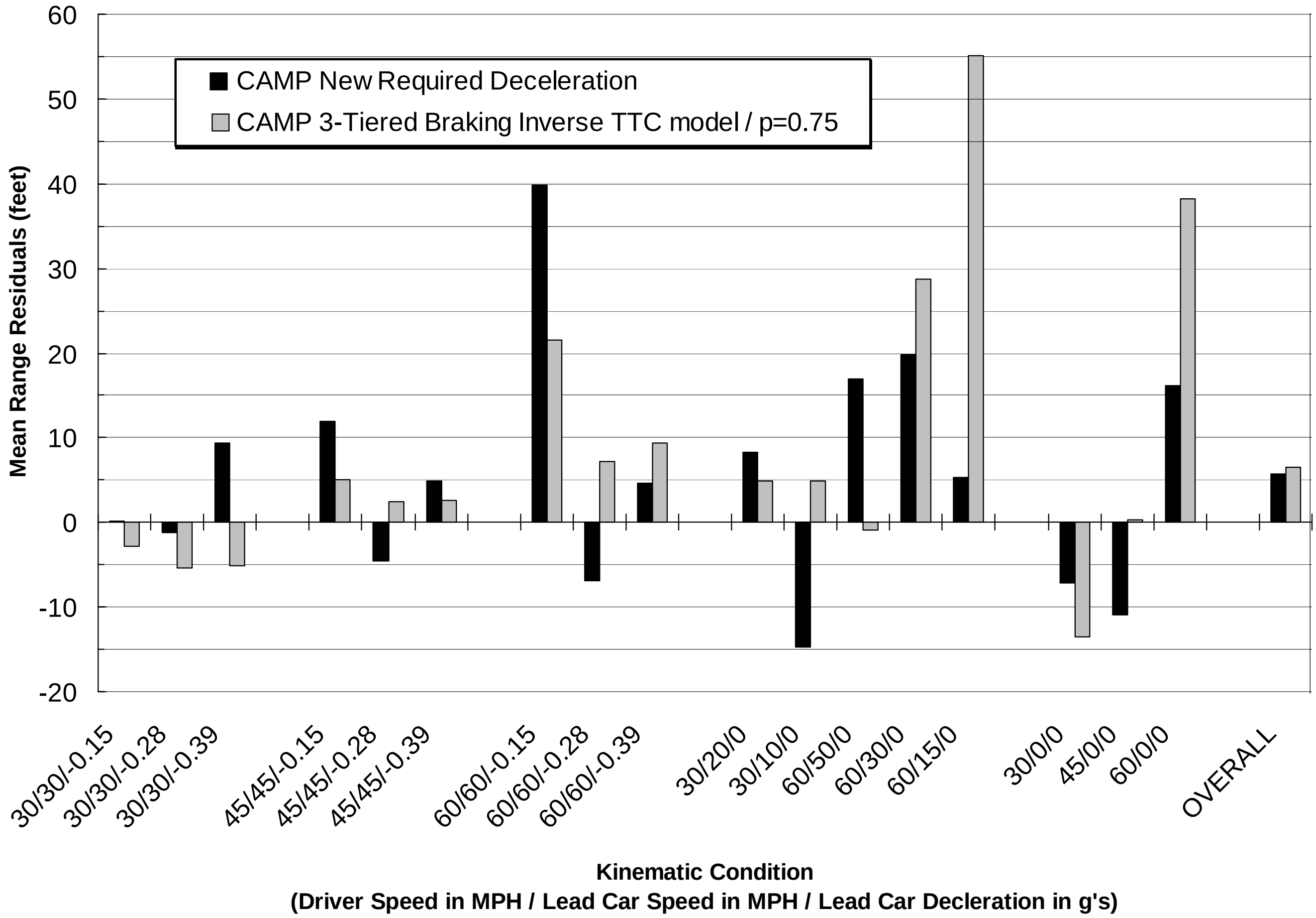


Figure 25. Percent of "Early" Brake Onset Predictions for Each Model Across Kinematic Conditions Using Last-Second, Normal Braking Data

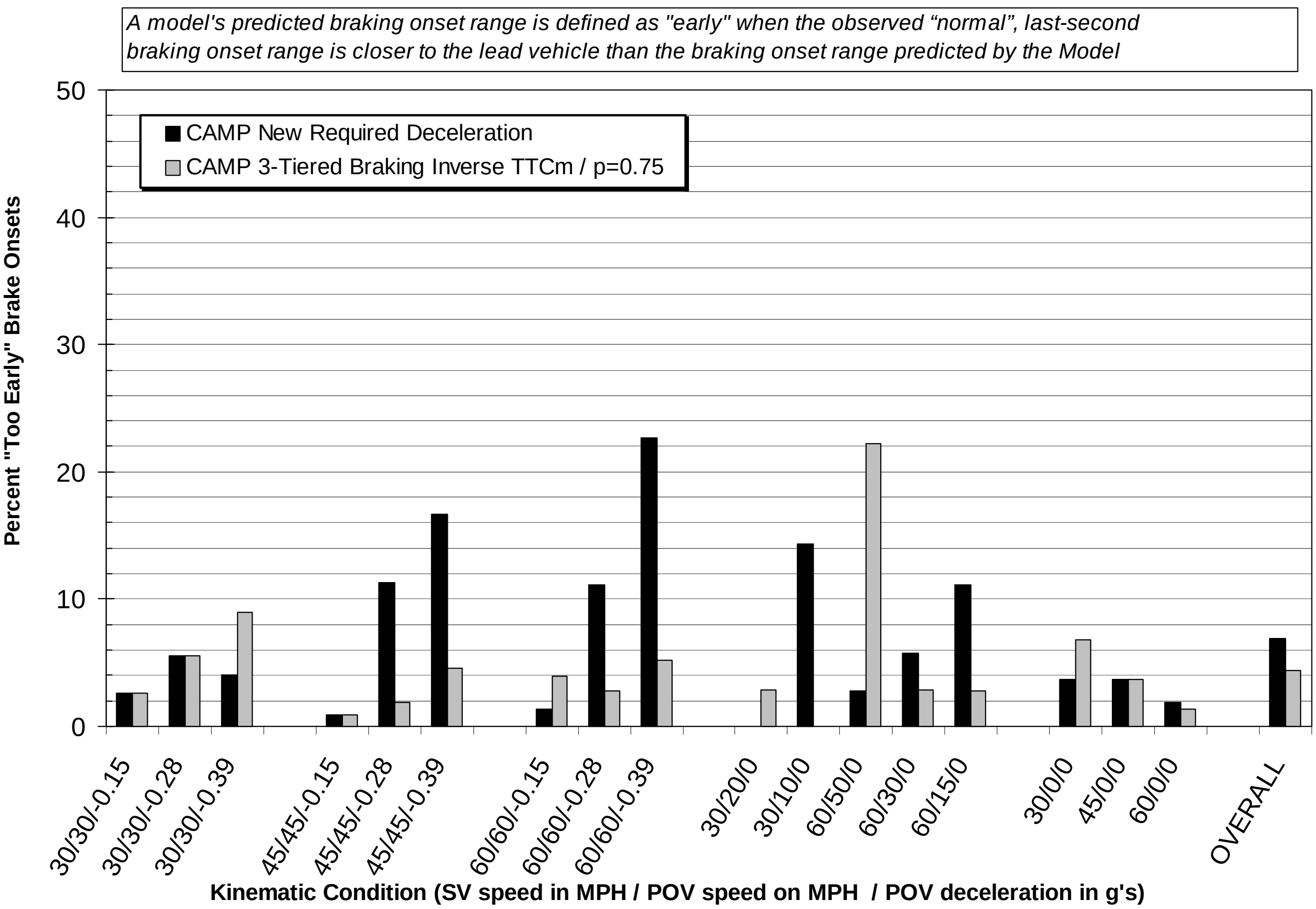
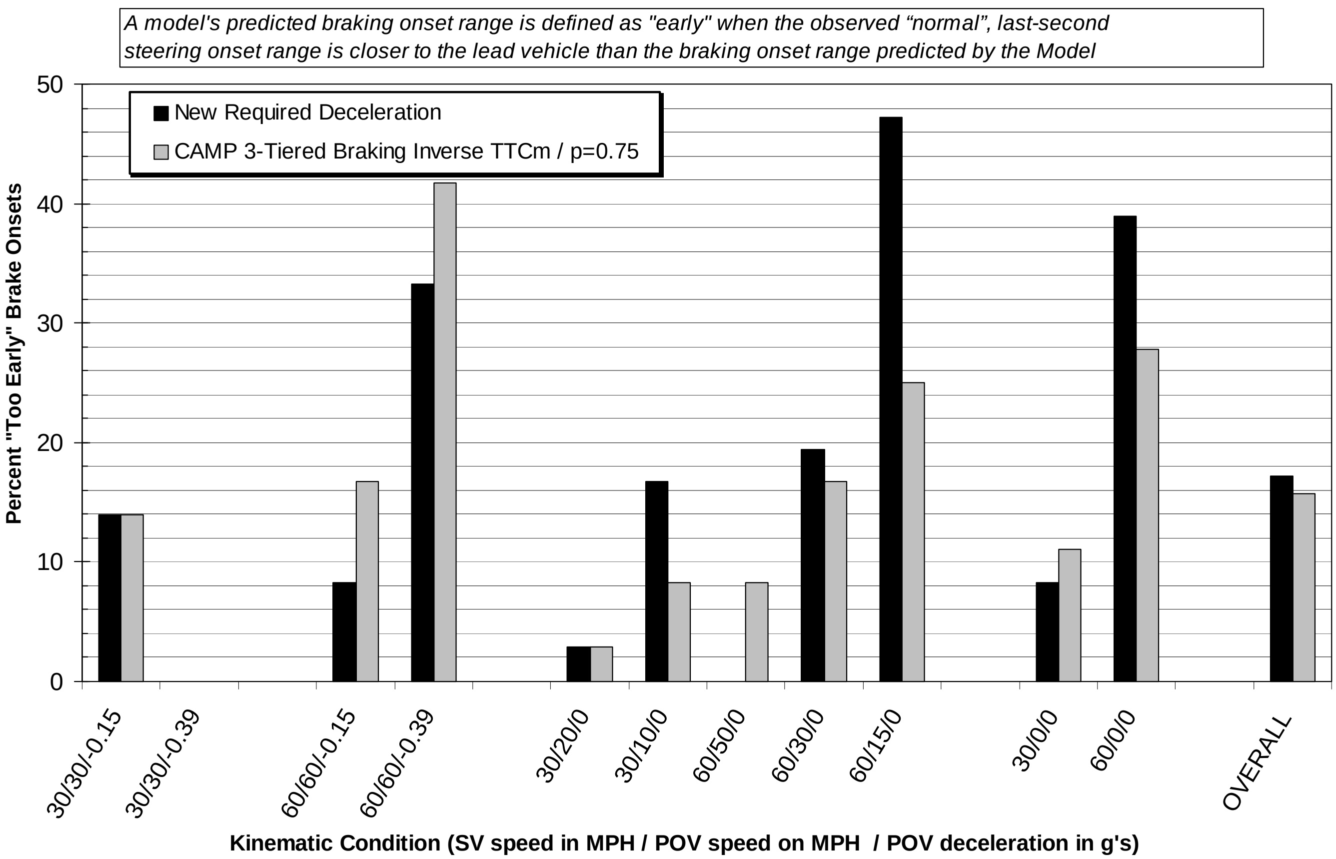


Figure 26. Percent of "Early" Brake Onset Predictions for Various Models Across Kinematic Conditions Using Last-Second, Normal Steering Data



The more aggressive driver braking criterion assumed a "late" predicted "hard" braking onset range occurred whenever the predicted "hard" braking onset range by the model is smaller (or closer to the lead vehicle) than that required to execute a fixed 0.55 g (constant deceleration) stop. (Such a stop is considered an approximation of the upper limit of driver braking capabilities.). That is, the predicted hard braking onset range would be considered "late" if the range required the driver to stop with a constant deceleration value of higher than 0.55 g's (independent of vehicle-to-vehicle kinematic equations). This is subsequently referred to as the "*0.55 g Braking Assumption*" criterion.

The less aggressive driver braking criterion assumed a "late" predicted "hard" braking onset range occurred whenever the predicted "hard" braking onset range by the model is smaller (or closer to the lead vehicle) than that predicted by the *CAMP Actual Deceleration Parameter* (*ADP*) equation developed in the previous CAMP FCW Project (Kiefer et al., 1999). This equation was based on 15th percentile (on the less aggressive end) of observed driver deceleration values during last-second hard braking at 30, 45, and 60 MPH speeds when the lead vehicle braked at 0.39 g's. This equation is shown below, which varies only with driver speed:

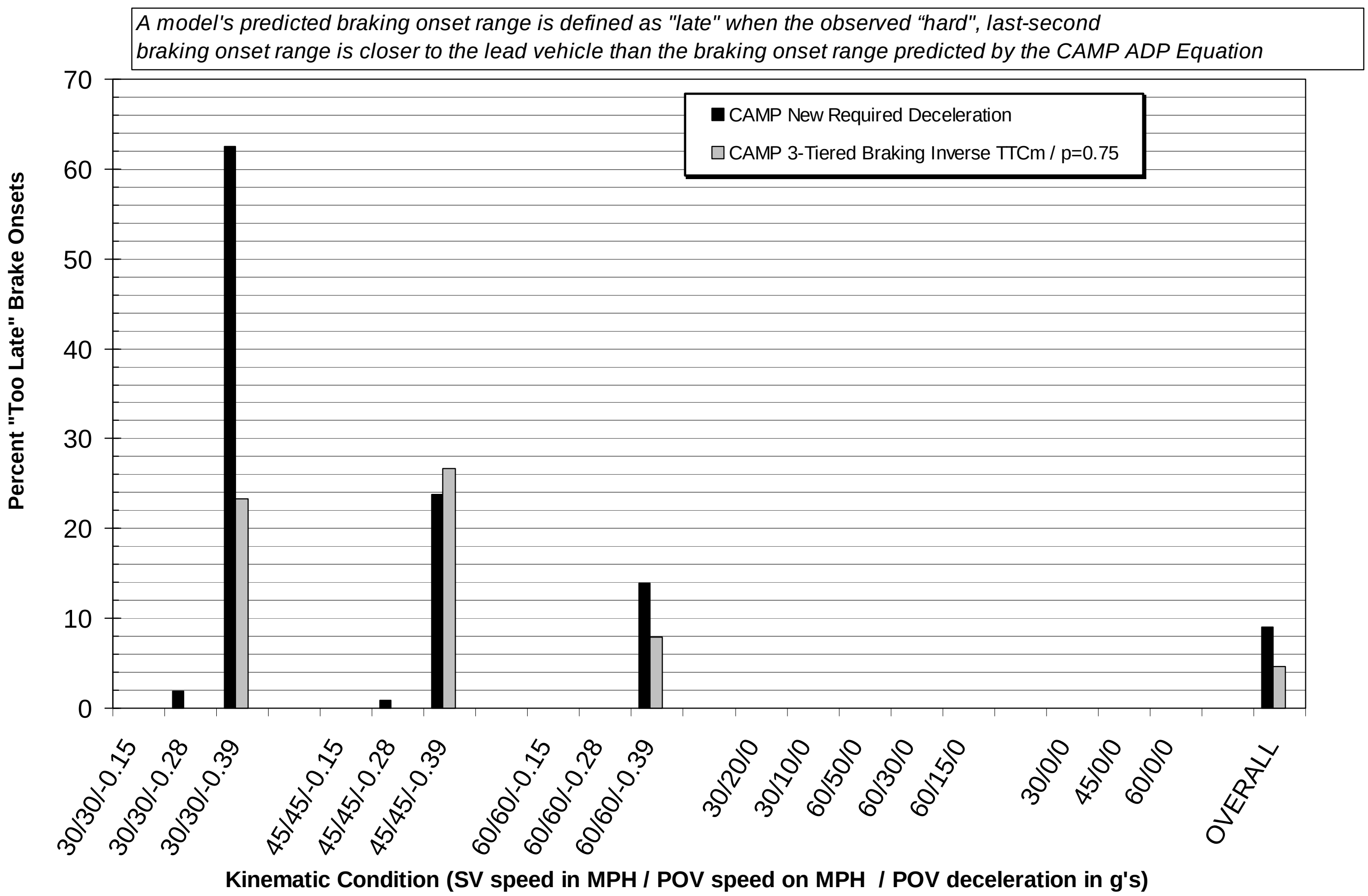
required decel. (g) = -0.260 - 0.00325(driver speed in MPH)

At driver speeds of 30, 45, and 60 MPH, this equation generates assumed driver deceleration values of 0.36, 0.41, and 0.45 g's, respectively. So for example, at a 30 MPH speed, the hard braking onset range would be considered "late" if the range required the driver to stop with a constant deceleration value of higher than 0.36 g's. It should be stressed that although this equation was developed with the notion of accommodating a high percentile of driver braking capabilities, this equation is unlikely to strictly represent such capabilities due to potential differences between last-second "hard" braking behavior observed under experimental conditions and actual driver braking capabilities. A more detailed rationale for this equation can be found in the previous Kiefer et al. work.

Results for "late" brake onset rates using the 0.55 g Braking Assumption criterion indicated "late" brake onset predictions occurred only in the 60/60/0.39, with rates of 0.7% for both models. The results for the CAMP ADP Equation criterion are shown in Figure 27. Overall, results indicated a lower overall "late" rate with the 3-Tiered Inverse TTC Model than the New Required Deceleration Model (4.6% versus 9.0% "late" rates). Recall, the corresponding overall "early" brake onset rates reported above (based on "normal" braking data) were 4.4% and 6.9%, respectively. Hence, this "early"/"late" inherent trade-off appears to favor the 3-Tiered Inverse TTC Model over the New Required Deceleration Model. It is also worth noting that the observed difference between these models in "late" rates (with the CAMP ADP Equation criterion) can be largely attributed to the 30/30/0.39 kinematic condition. In addition, and not surprisingly, these "late" occurrences are restricted to POV Decelerating Trials when the lead vehicle was braking at the two highest POV braking levels examined.

It should be noted that another potential driver braking criterion was considered for calculating "late" rates. This criterion assumed a "late" predicted "hard" braking onset range occurred whenever the predicted "hard" braking onset range by the model is smaller (or closer to the lead vehicle) than the observed "hard" braking onset range. However, as noted above, the concern was such a criterion would reflect "late" occurrences relative to driver-preferred hard braking onsets rather than driver braking capabilities. Such an approach would result in assuming relatively low required decelerations (less than 0.10 g's) under some of the kinematic conditions examined.

<u>Figure 27</u>. Percent of "Late" Brake Onset Predictions for Each Model Across Kinematic Conditions Based on CAMP Actual Deceleration Parameter (ADP) Equation



Domain of Validity Considerations

A domain of validity check was also performed for the New Required Deceleration Model and the 3-Tiered Inverse TTC Model. For each model, three separate cases were examined: constant ΔV scenarios (which include approaches to stationary objects), scenarios involving a POV decelerating at 0.2 g's, and scenarios involving a POV decelerating at 0.4 g's. For each of these three cases, 2700 combinations of vehicle-to-vehicle kinematic conditions were examined, including a wide range of driver speed (ranging from 20 to 75 MPH) and lead vehicle speed (ranging from 0 to 75 MPH) combinations. The domain of validity plots were created from this data which show "iso" required deceleration and range contours at predicted braking onset for each model. In these "iso" contours, the desired outcome is a family of continuous contours with reasonable required deceleration values at braking onset (i.e., not too small or not too large) smoothly varying without unexpected changes in slope. This smoothness is desirable for two reasons. First, it suggests that drivers would find the crash alert timing based on the model to be consistent in similar vehicle-to-vehicle kinematic conditions (or conflict situations), since the alert timing would not change greatly with small changes in kinematic conditions. Second, the observed smoothness provides assurance that the model does not have any unexpected behavior within the wide range of conditions examined in this domain of validity check.

The domain of validity figures for the 3-Tiered Inverse TTC Model employing the required deceleration measure are shown in Figure 28, Figure 29, and Figure 30 for the constant ΔV scenarios, scenarios involving a POV decelerating at 0.2 g's, and scenarios involving a POV decelerating at 0.4 g's, respectively. The corresponding domain of validity figures for the New Required Deceleration Model are shown in Figure 31, Figure 32, and Figure 33, respectively. In addition, the differences in braking onset predictions for these two models are shown in Figure 34, Figure 35, and Figure 36, respectively. For the interested reader, the domain of validity figures for both models employing the range measure are shown in Figure 37 through Figure 42.

It should be noted that, for the purposes of these domain of validity analyses, it assumed that the FCW system has perfect, real-time knowledge of range to the lead vehicle, as well as perfect knowledge of the speeds and acceleration of both the lead and following vehicles. Hence, any effects of errors in the measurement or estimation of these quantities are left unaddressed, and practical sensor range limitations are not considered (see Figure 37 through Figure 42 for range predictions for potential consequences of these limitations). It should also be noted that this domain of validity discussion surrounding brake onset predictions does not address issues surrounding the consequences of differences between the kinematic conditions projected at brake onset after some "delay time" (e.g., 1.6 seconds) into the future versus the actual kinematic conditions observed during and at the end this delay time interval. This delay time component (which includes the assumed driver brake reaction time for an inattentive or distracted driver, brake system time delays, and interface onset delays) is used to calculate a delay time range, which is then added to the assumed braking onset range to create the actual alert onset range. The underlying assumptions used in projecting future kinematic conditions are an important aspect of a crash alert timing approach, which again, are not addressed here.

The domain of validity plots using the required deceleration measure are shown in Figure 28 through Figure 33. These plots indicate that both models are relatively robust over the wide range of kinematic conditions considered. The plots for the 3-Tiered Inverse TTC model are particularly valuable because predictions from this model are mapped into a variable (required deceleration) that can be more directly applied for understanding and quantifying dynamic braking situations. For both models, required decelerations at brake onset remain under 0.45 g's in nearly all conditions examined, with the exceptions occurring under relatively extreme kinematic conditions with the New Required Deceleration Model. For

Figure 28. **Domain of Validity Check for the CAMP 3-Tiered Inverse TTC model (p=0.75): Required Deceleration at Braking Onset Under Conditions Where Both Vehicles are Moving at a Constant Speed.**

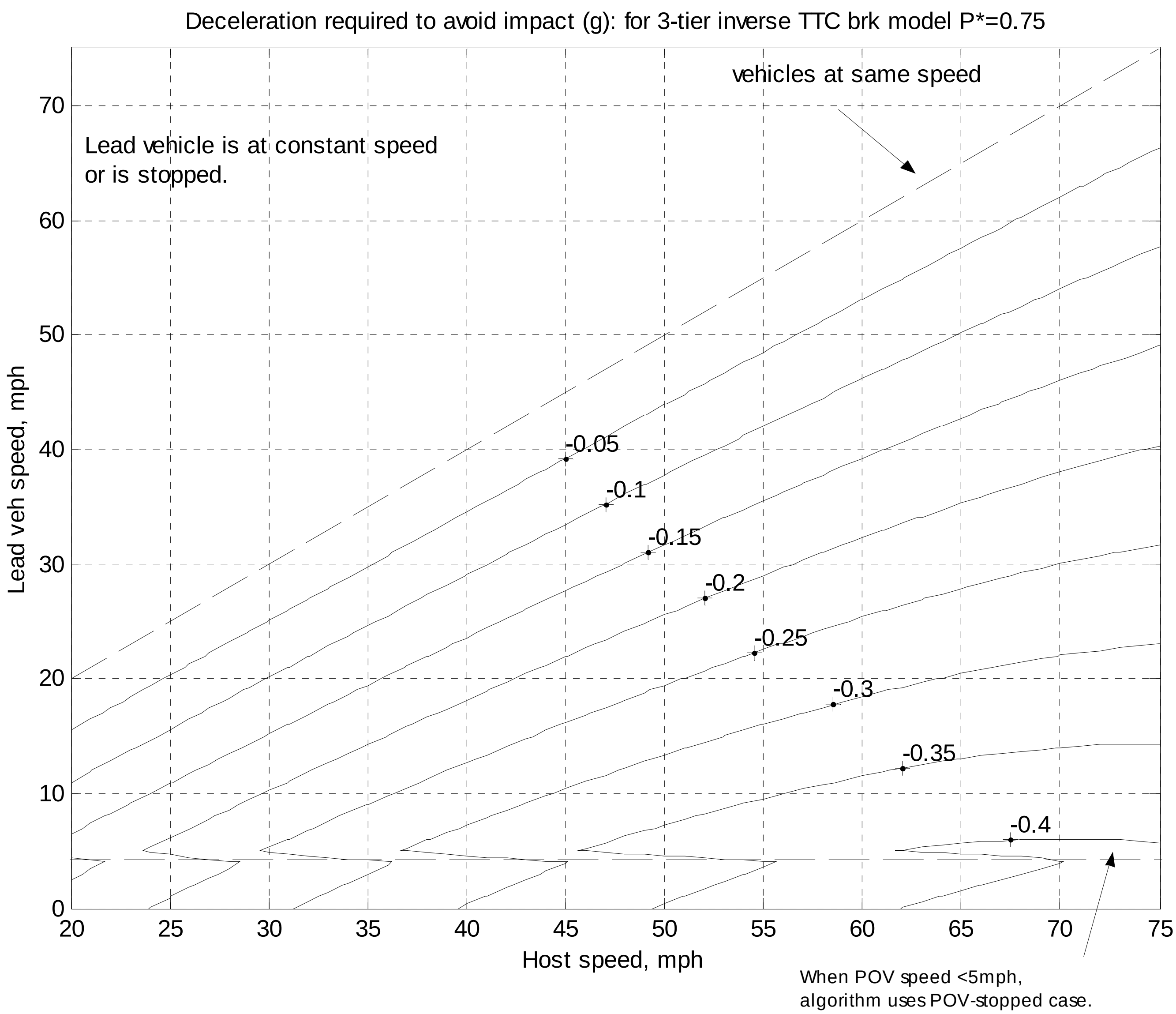
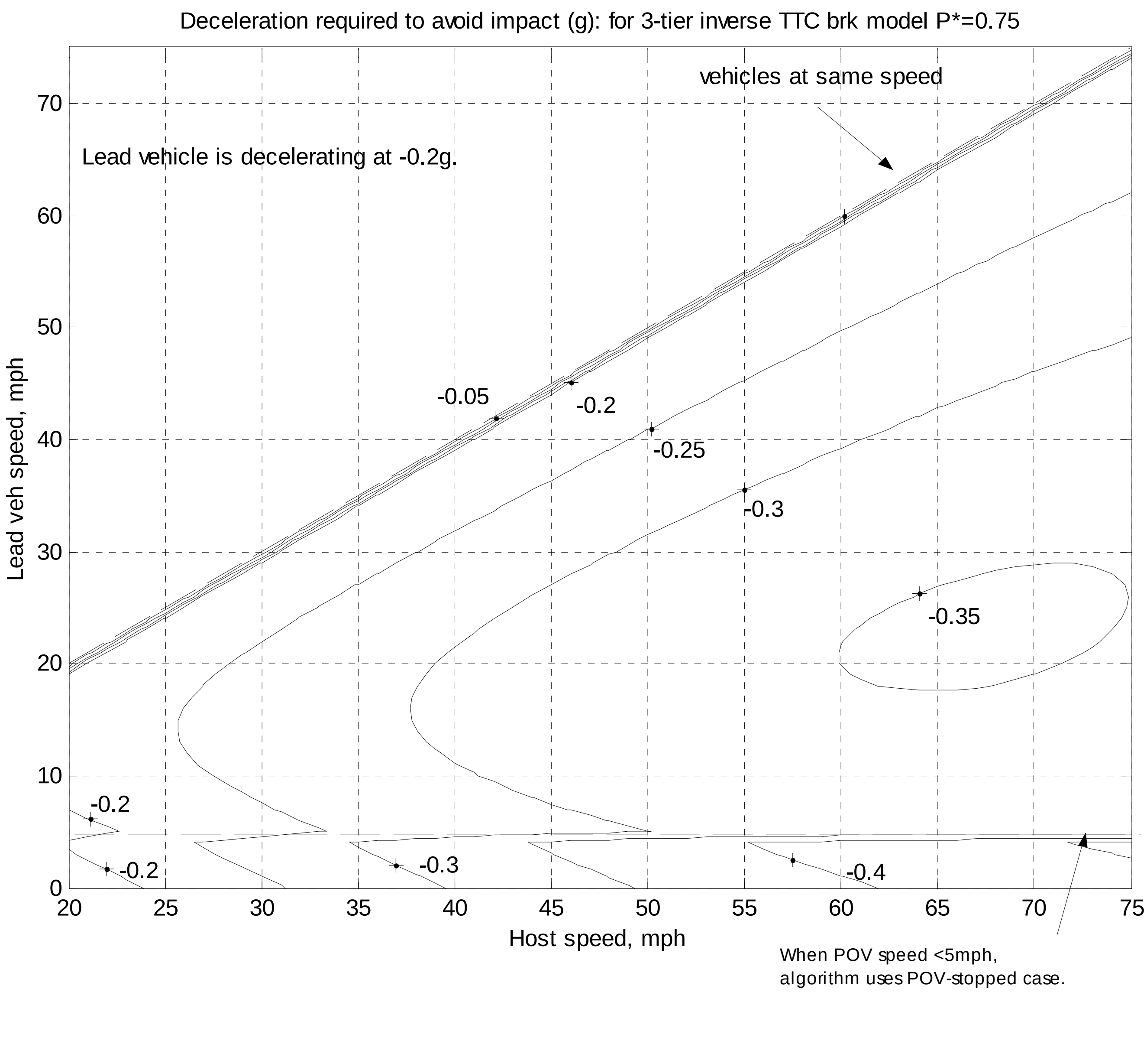
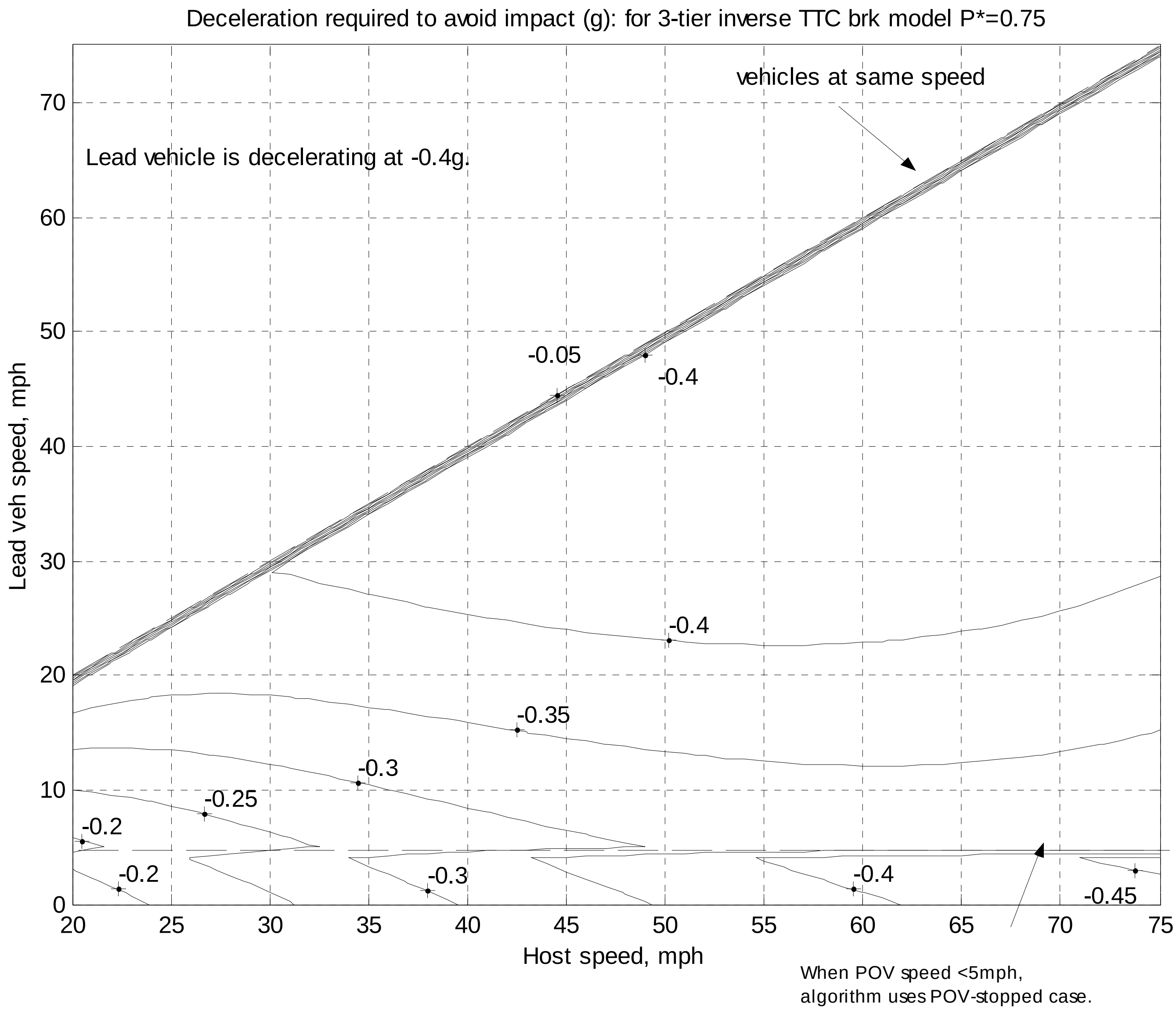


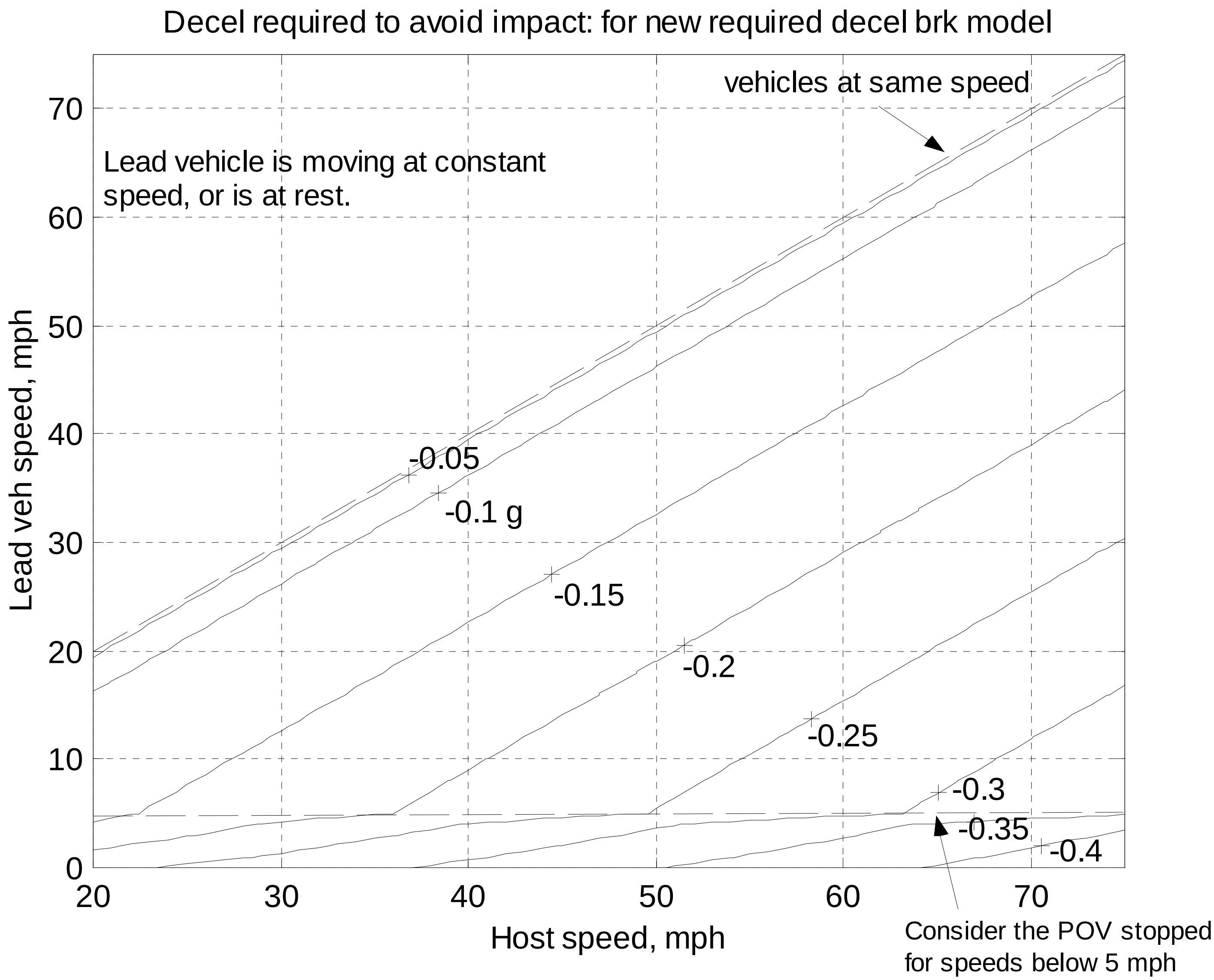
Figure 29. Domain of Validity Check for the CAMP 3-Tiered Inverse TTC Model (p=0.75): Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.2 g's.



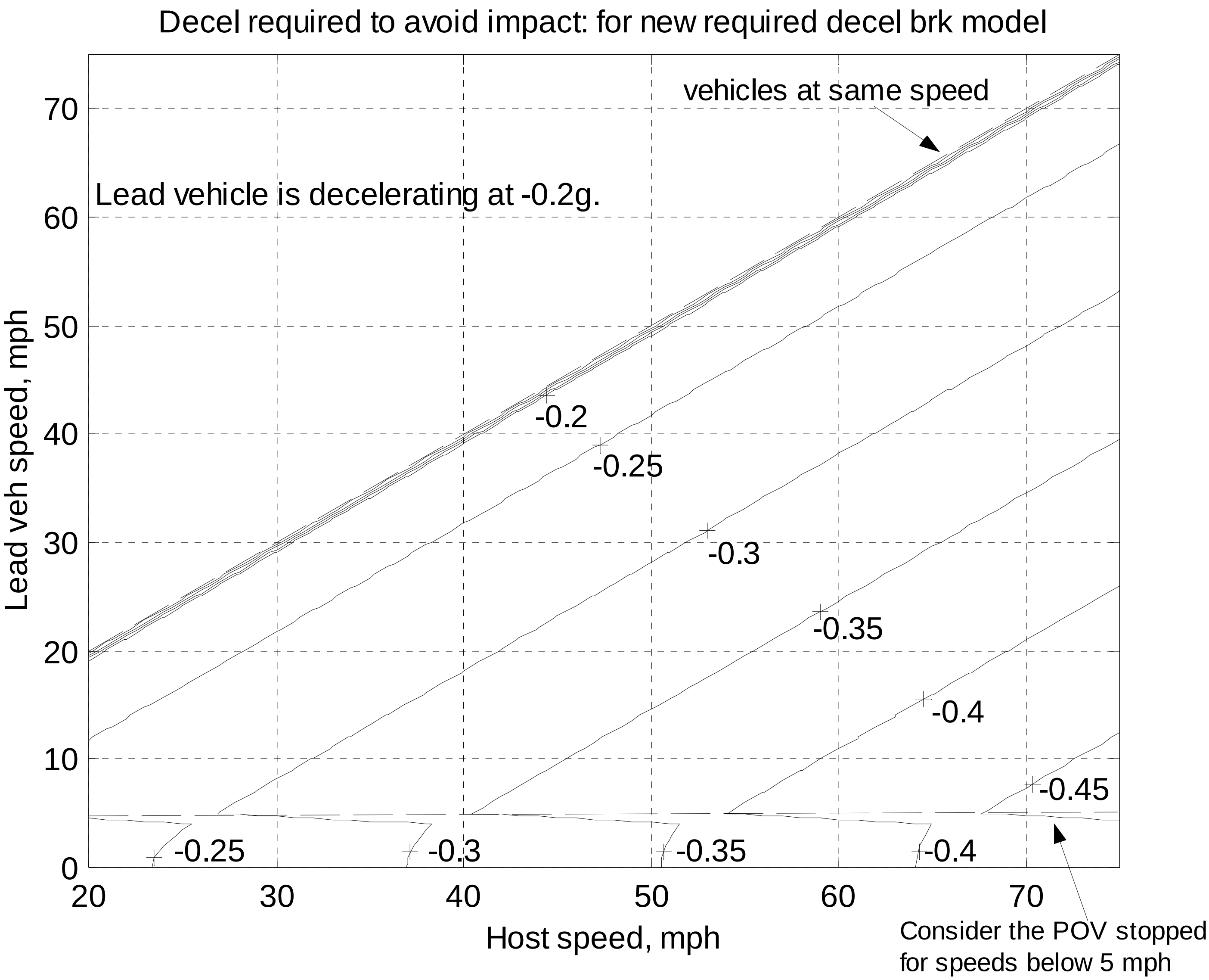
<u>Figure 30</u>. Domain of Validity Check for the CAMP 3-Tiered Inverse TTC Model (p=0.75): Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.4 g's.



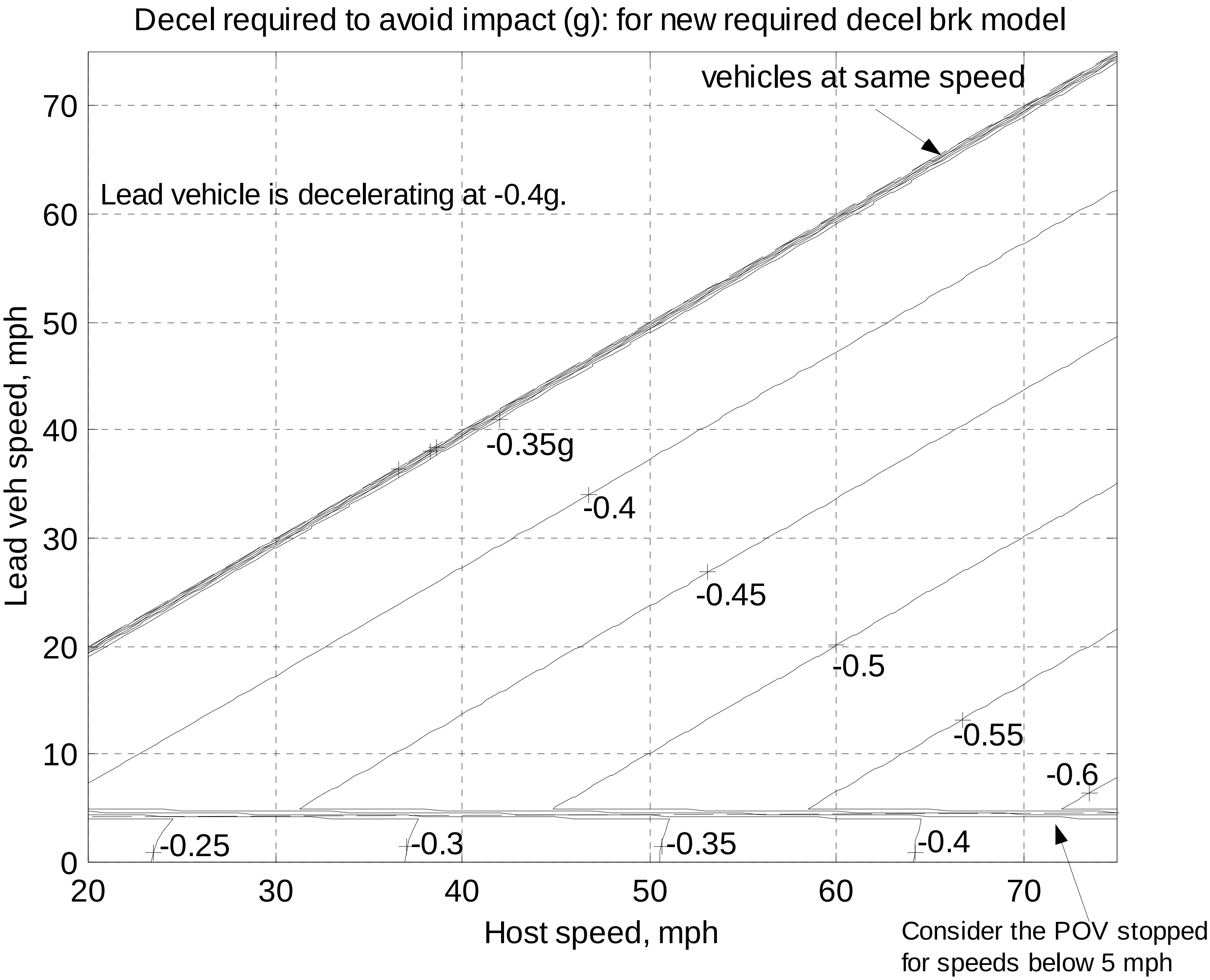
<u>Figure 31</u>. Domain of Validity Check for the CAMP New Required Deceleration Model: Required Deceleration at Braking Onset Under Conditions Where Both Vehicles are Moving at a Constant Speed.



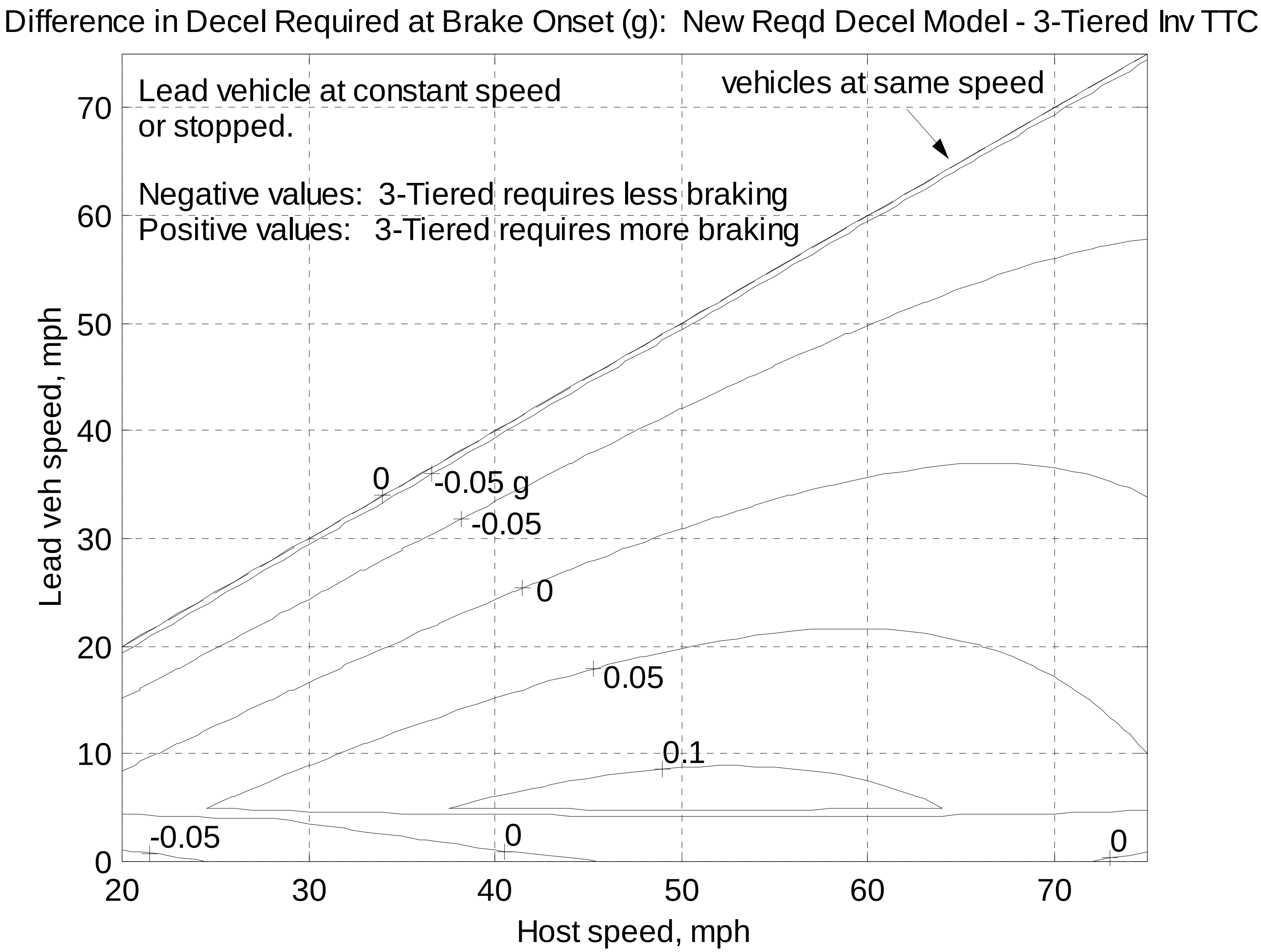
<u>Figure 32</u>. Domain of Validity Check for the CAMP New Required Deceleration Model: Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.2 g's.



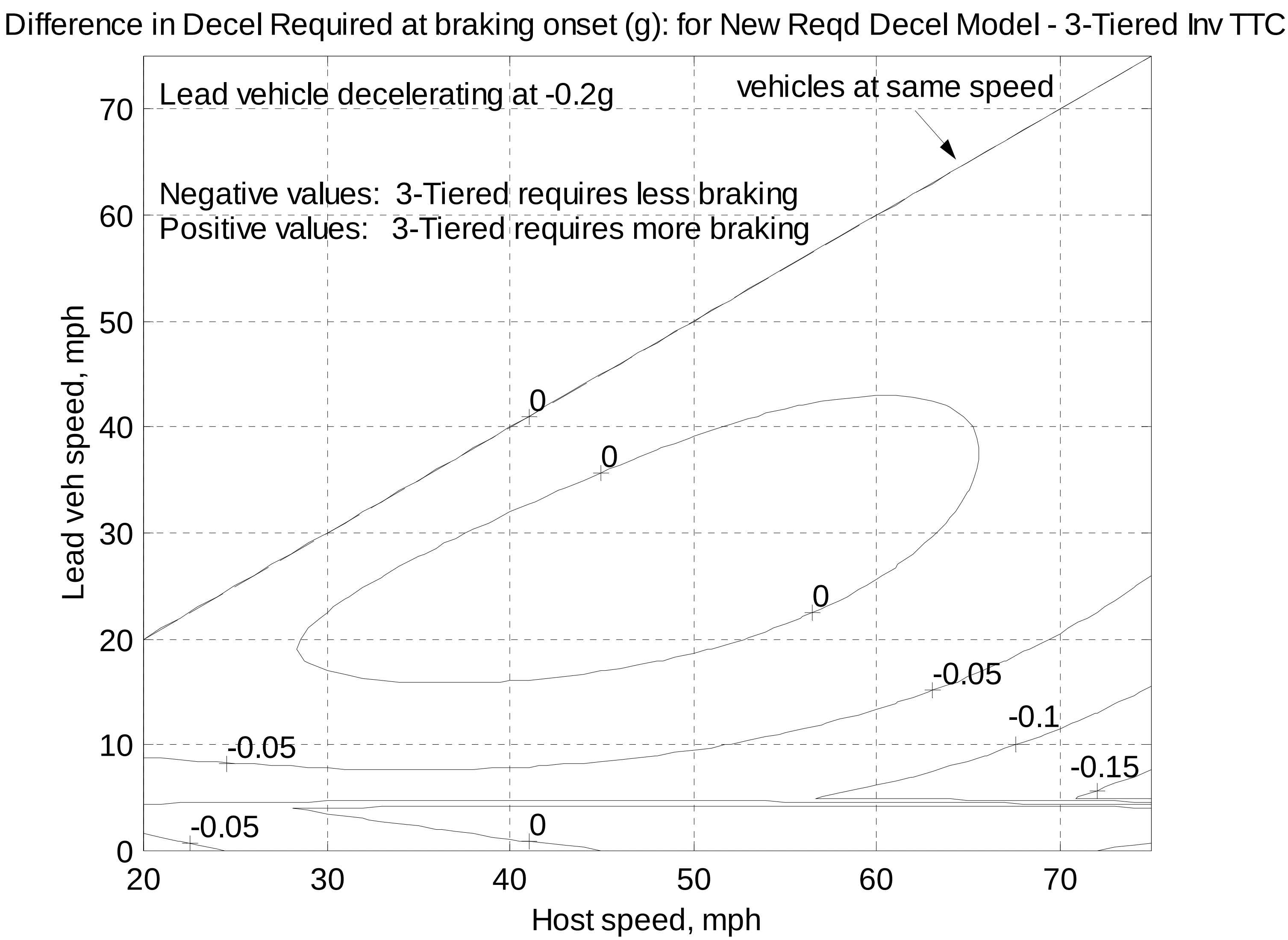
<u>Figure 33</u>. Domain of Validity Check for the CAMP New Required Deceleration Model: Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.4 g's.



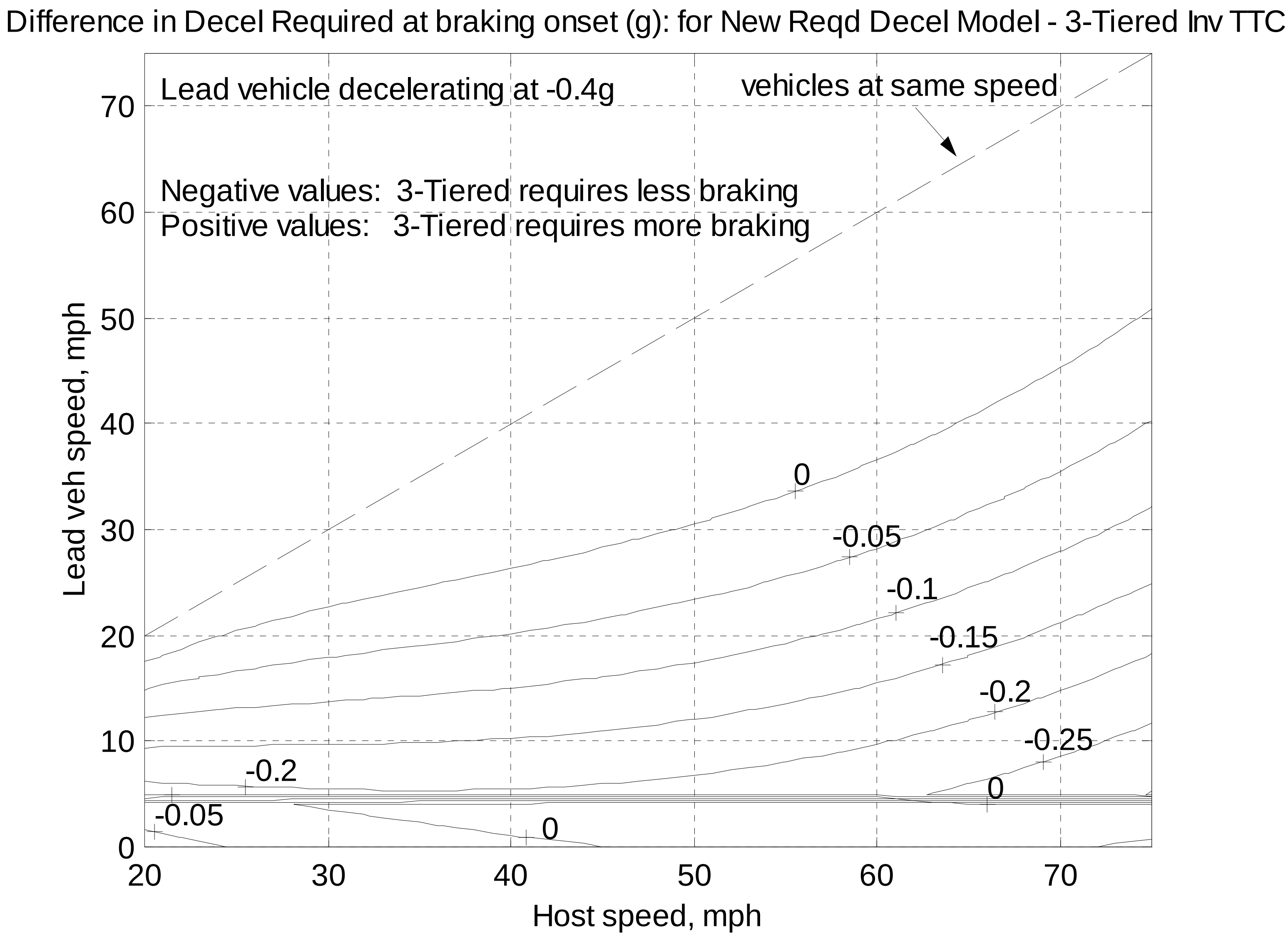
<u>Figure 34</u>. Difference in Model Predictions for Required Deceleration at Braking Onset Under Conditions Where Both Vehicles are Moving at a Constant Speed.



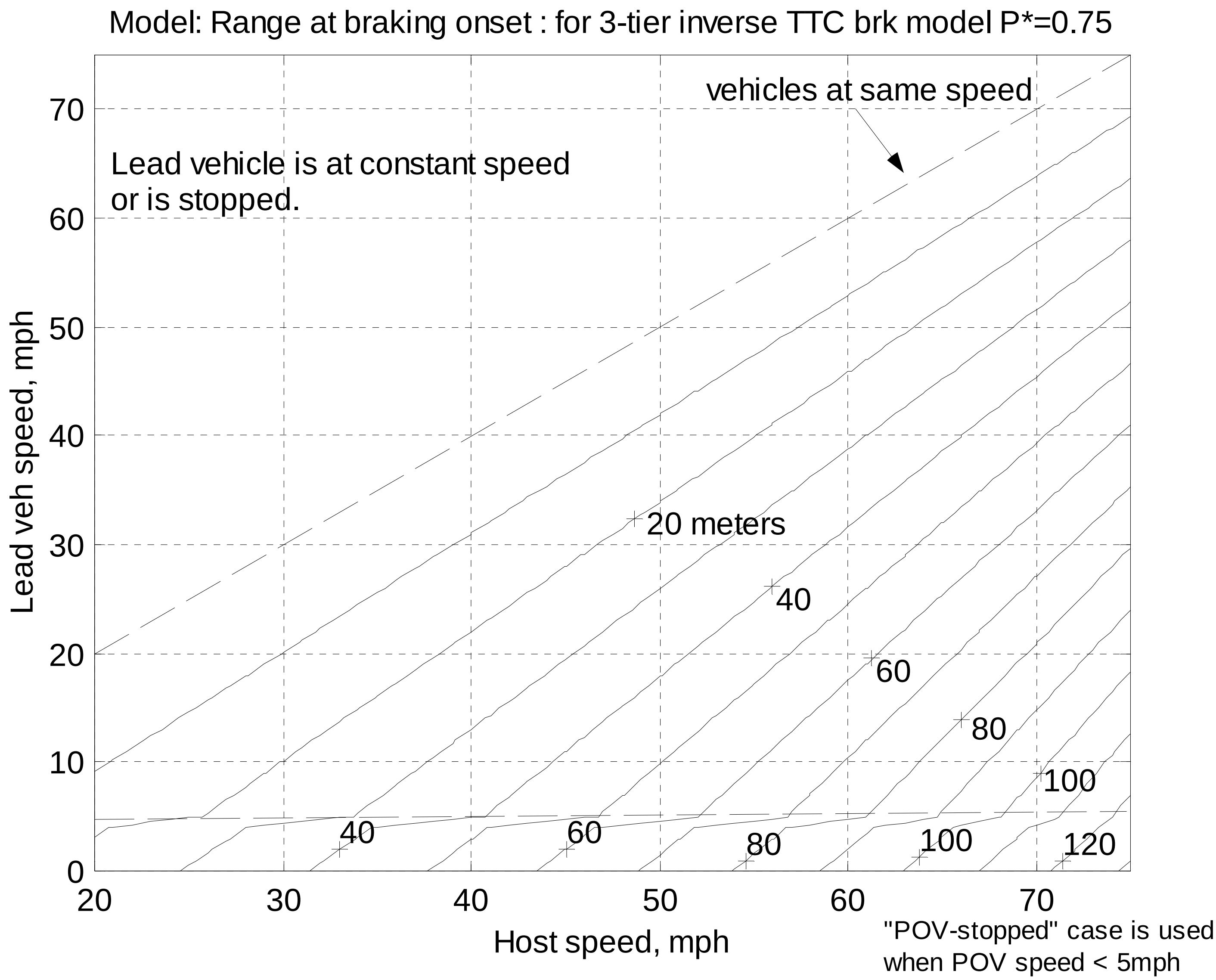
<u>Figure 35</u>. Difference in Model Predictions for Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.2 g's.



<u>Figure 36</u>. Difference in Model Predictions for Required Deceleration at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.4 g's.



<u>Figure 37</u>. Domain of Validity Check for the CAMP 3-Tiered Inverse TTC model (p=0.75): Range at Braking Onset as a Function Under Conditions Where Both Vehicles are Moving at a Constant Speed.



<u>Figure 38</u>. Domain of Validity Check for the CAMP 3-Tiered Inverse TTC Model (p=0.75): Range at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.2 g's.

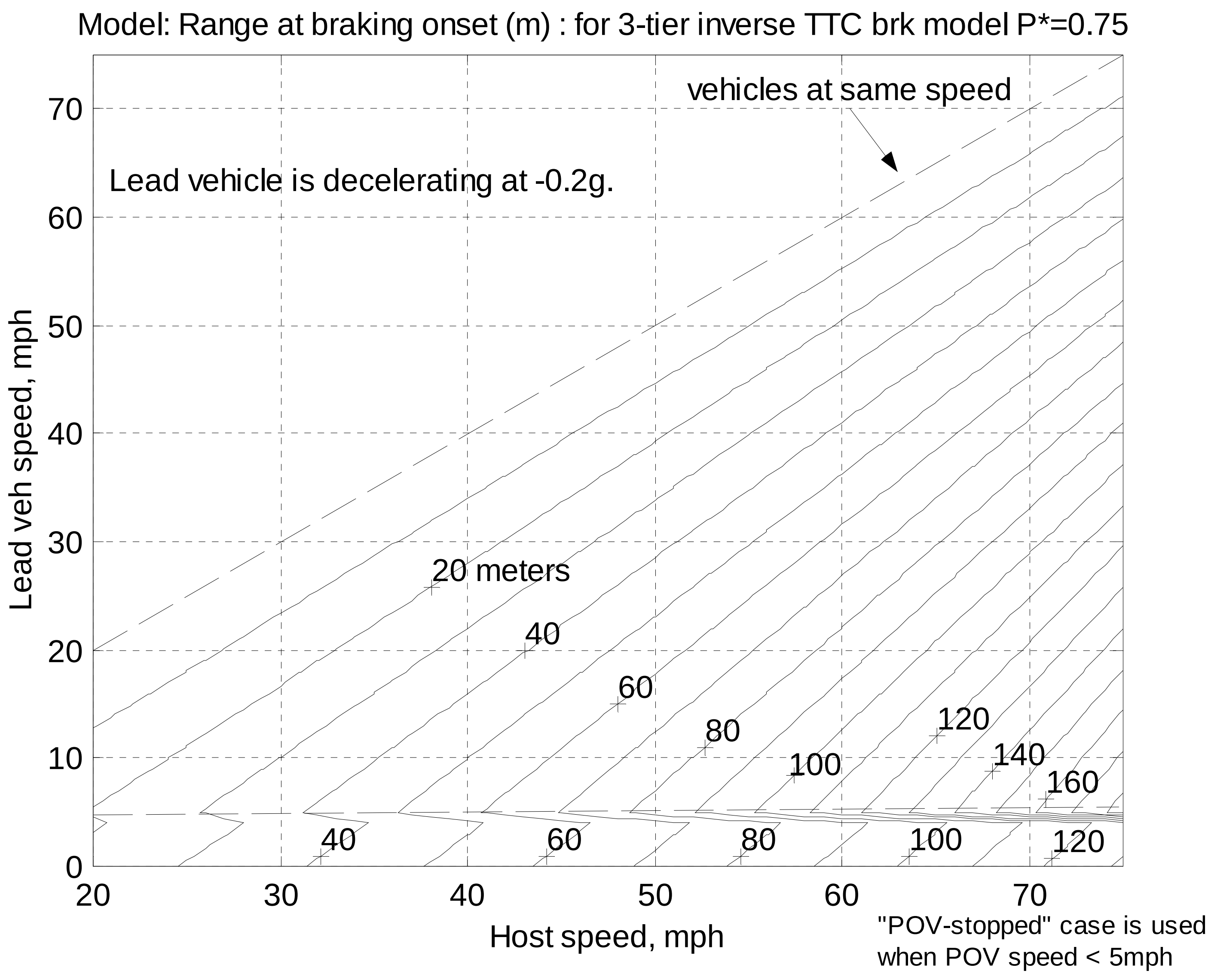
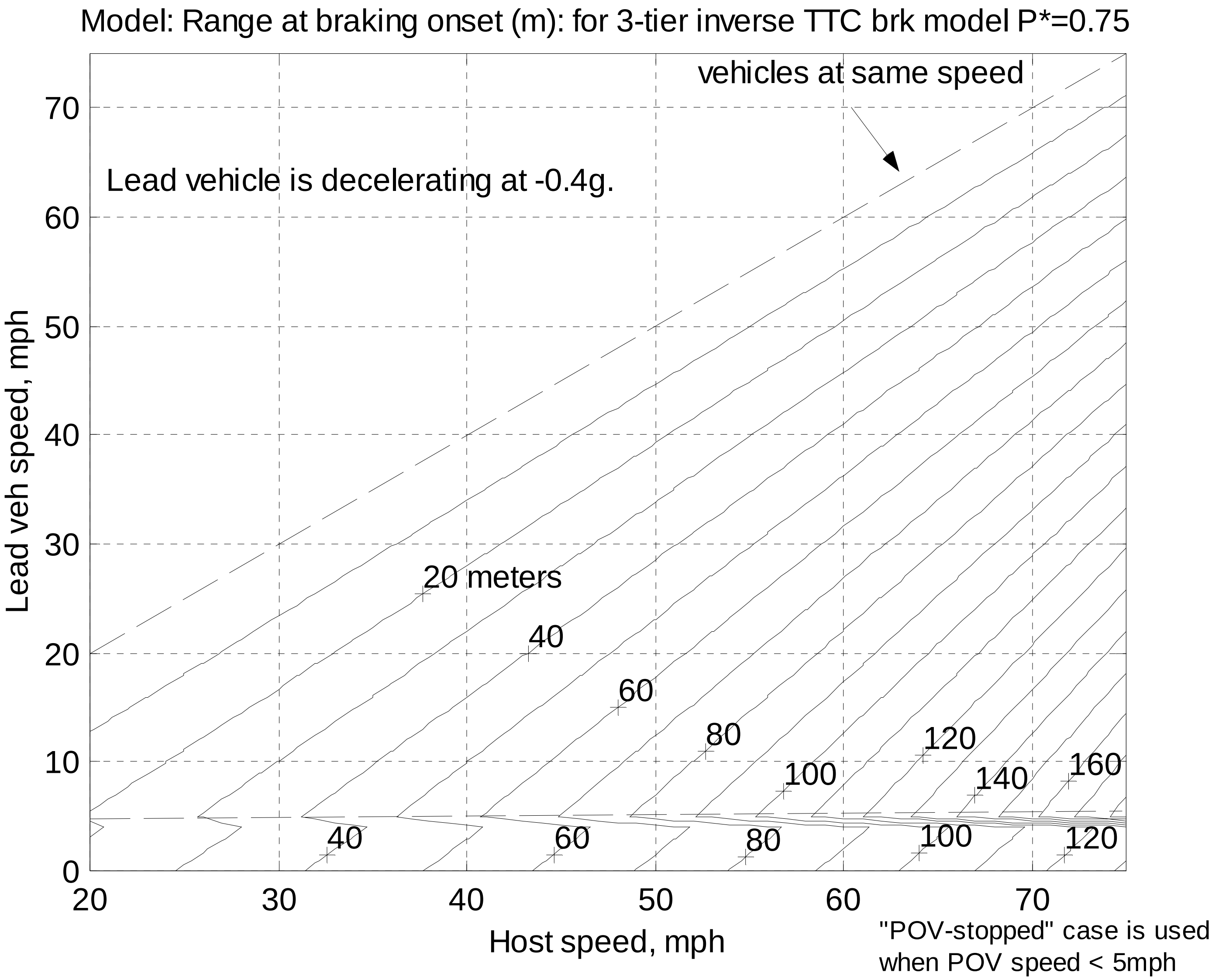
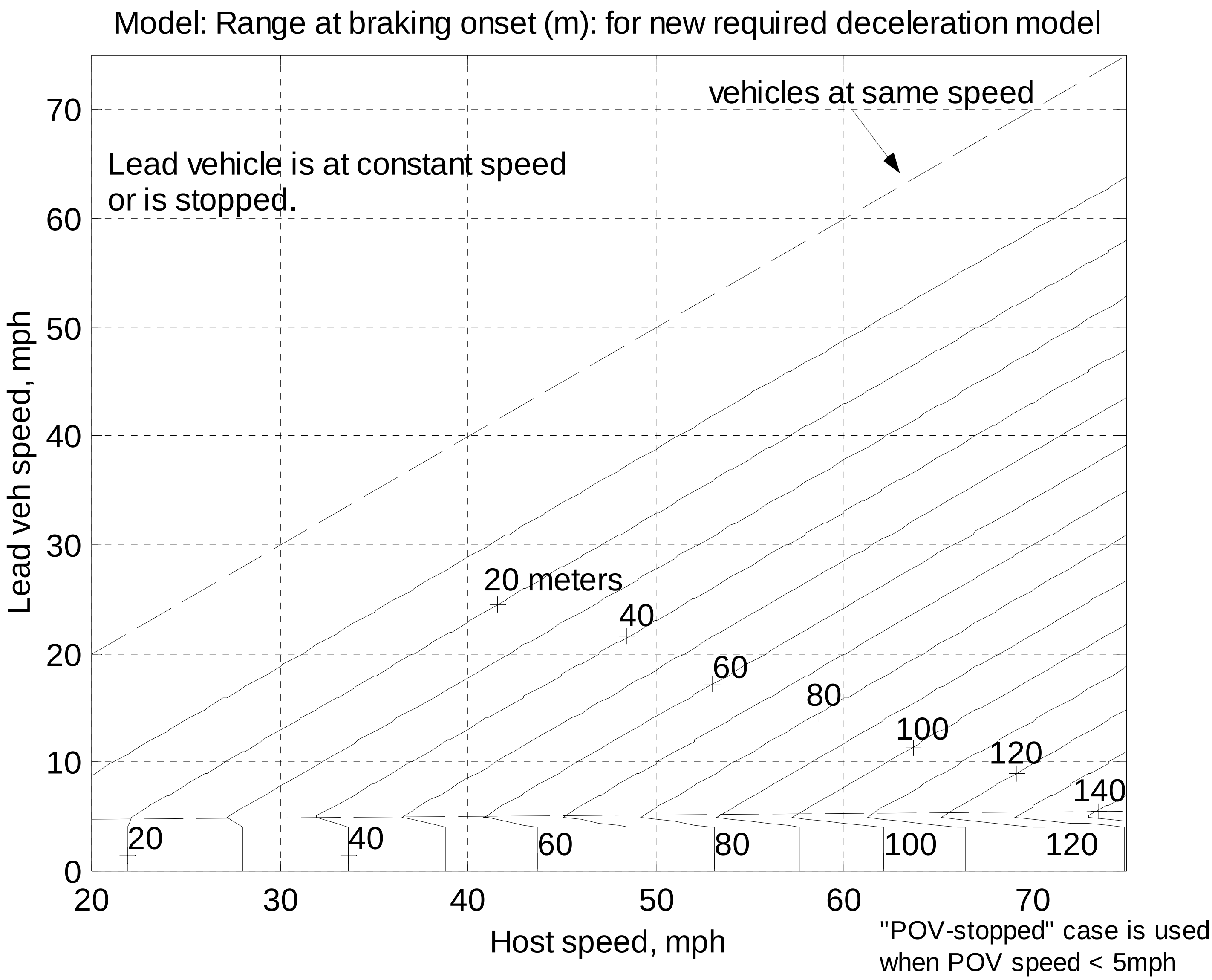


Figure 39. Domain of Validity Check for the CAMP 3-Tiered Inverse TTC Model (p=0.75): Range at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.4 g's.



<u>Figure 40</u>. Domain of Validity Check for the CAMP New Required Deceleration Model: Range at Braking Onset Under Conditions Where Both Vehicles are Moving at a Constant Speed.



<u>Figure 41</u>. Domain of Validity Check for the CAMP New Required Deceleration Model: Range at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.2 g's.

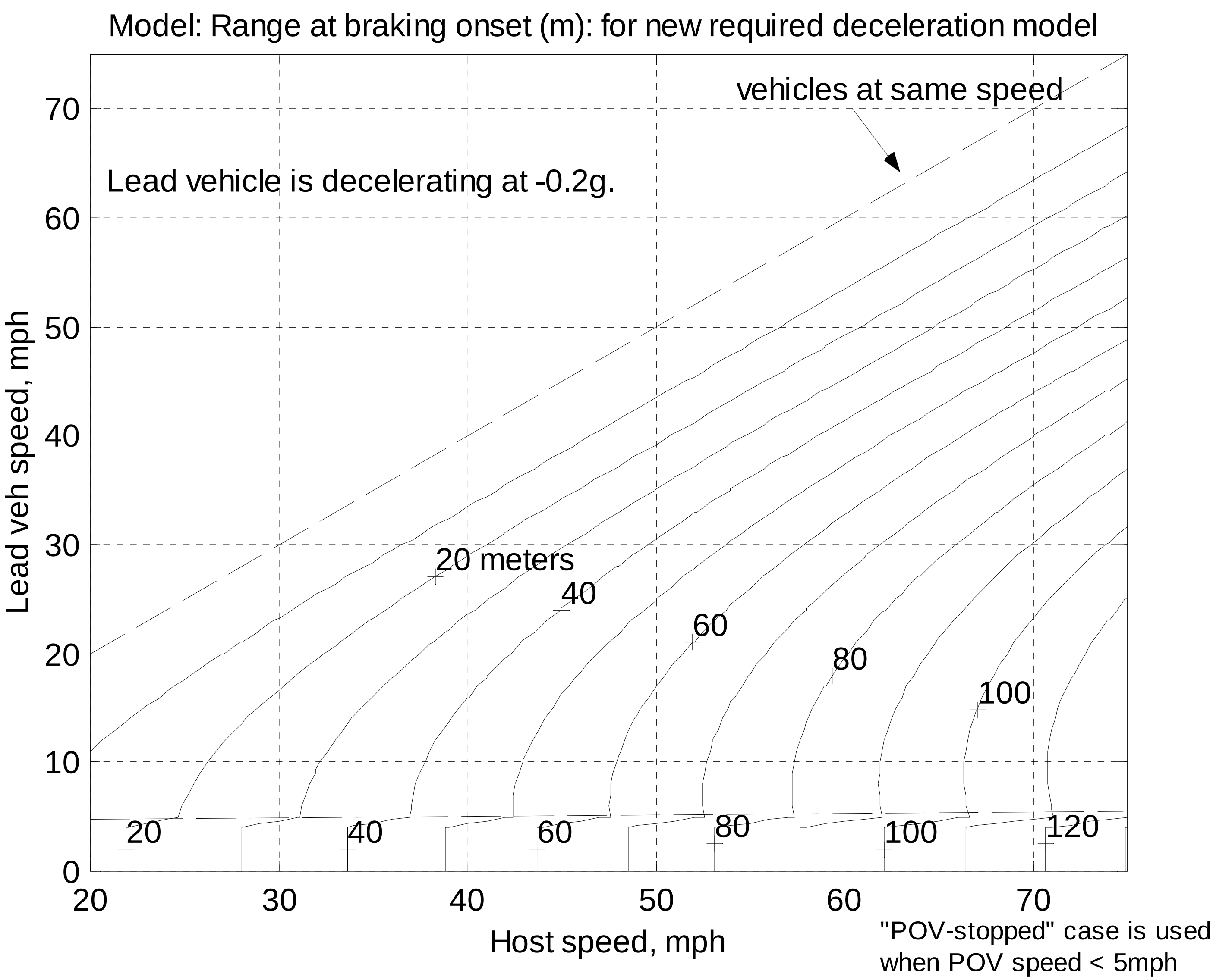
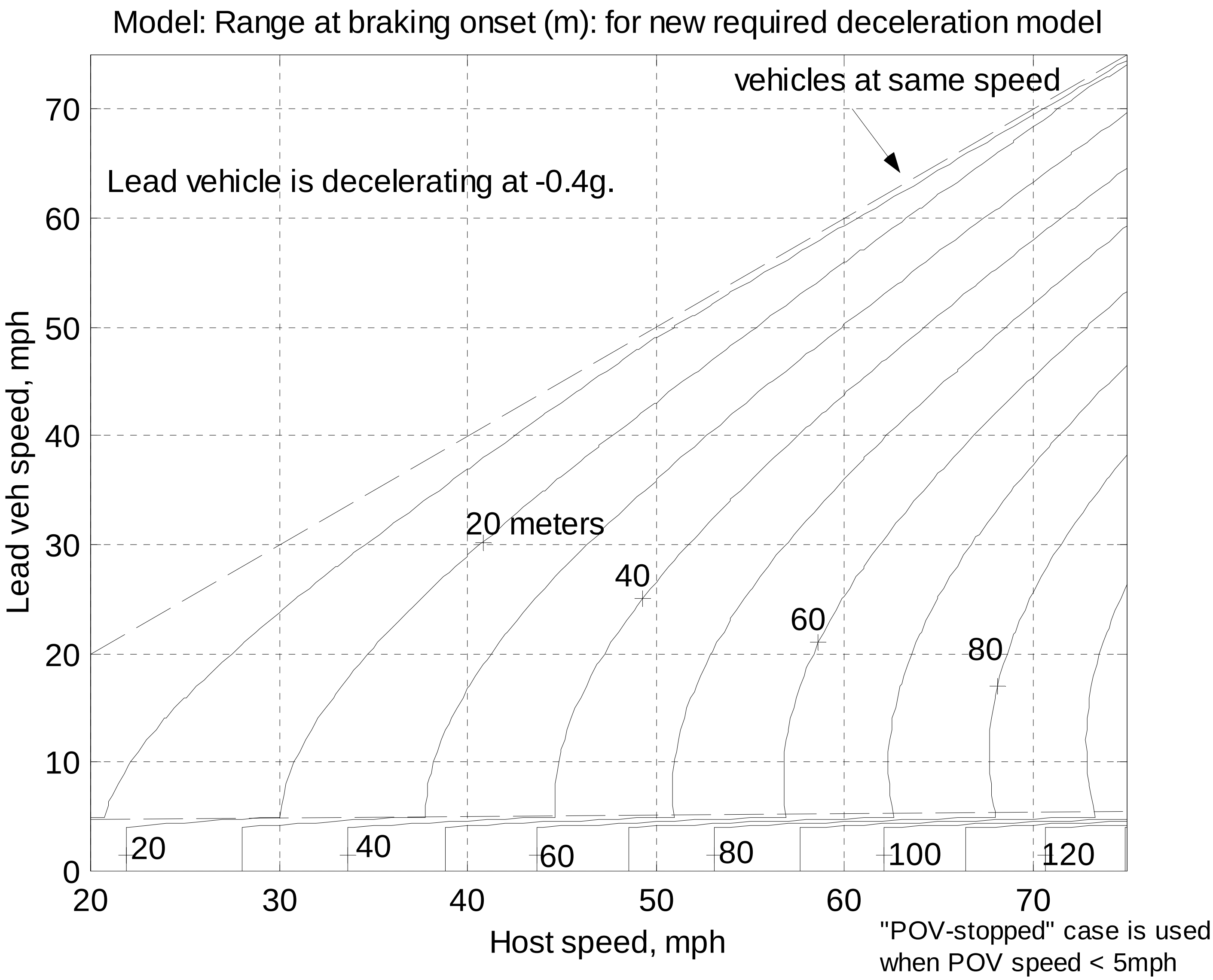


Figure 42. Domain of Validity Check for CAMP New Required Deceleration Model: Range at Braking Onset Under Conditions Where the Lead Vehicle is Decelerating at 0.4 g's.



example, Figure 33 shows that at high closing rates coupled with high lead vehicle deceleration values, (e.g., 70 mph approach to a vehicle traveling at 10 mph vehicle that is braking at –0.4 g's), required decelerations may exceed –0.55 g's. With respect to these exception conditions, it should be noted that these conditions are likely to be rare in real-world traffic, and that the FCW alert criterion may be satisfied before these extreme kinematic conditions are even reached.

Figure 34 through Figure 36 show the differences in required deceleration at brake onset predictions for the two models. These figures show that the two models are quite close in terms of brake onset predictions, with predictions falling generally within 0.05 g's of each other. The largest differences are over 0.20 g's, and are seen again at relatively extreme kinematic conditions. Figure 36 shows these differences in required deceleration at brake onset are most evident at high closing rates coupled with high lead vehicle deceleration values, (e.g., 70 mph approach to a vehicle traveling at 15 mph vehicle that is braking at –0.4 g's).

It should also be noted that these plots also reveal some discontinuities that would need to be addressed in the actual implementation of this models. Both models show discontinuities between the boundary of the lead vehicle moving and lead vehicle stationary cases. These discontinuities could be addressed in several ways, including by smoothing predictions between these two cases.

Summary and Conclusions

This research examined drivers' last-second braking and last-second steering (or lane-change) judgments under a wide range of vehicle-to-vehicle kinematic conditions. These judgments were characterized in terms of both deceleration-based (namely, required deceleration) and time-based (time-to-collision or TTC) approaches. There were two key findings that emerged from the observed last-second maneuver (braking and steering) onset behavior. First, the differences observed in last-second braking behavior as a function of test site, age, and gender were relatively small in magnitude, and hence, did not play a role in the subsequent modeling process. Second, differences were observed between last-second braking and last-second steering onsets, and these differences clearly indicate that the relative timing of last-second braking onset versus last-second steering onset is highly dependent on the kinematic conditions. Under nearly all 60 MPH conditions examined, mean steering onsets when drivers were instructed to change lanes at the last second possible tended to occur later (i.e., were more aggressive) than mean braking onsets when drivers were instructed to brake at the last second possible using hard braking pressure. (This difference was not observed under the 30 MPH speed conditions examined.) Furthermore, the magnitude of this effect increased as the difference in speed between the lead and following vehicles (or delta velocity) increased. The consequence of this effect (i.e., last-second steering onsets occurring later than last-second braking onsets) on potential nuisance alerts during intentional lane changes will be discussed shortly in the context of braking onset model predictions.

From a methodological and driver behavior modeling perspective, it is worthwhile to note that as was first discovered in the previous CAMP FCW work (Kiefer et al., 1999), the 95th percentile required deceleration values for last-second braking judgments when using "normal" braking pressure correspond very closely to the 50th percentile required deceleration values for last-second braking judgments when using "hard" braking pressure. Perhaps of greater interest, the current work established that this relationship (95th "normal" = 50th "hard") was fairly robust under last-second lane change conditions.

These data were then modeled for predicting hard braking onset (or driver deceleration behavior), which is one of two driver behavior parameters needed for a crash alert timing approach (the other parameter being driver brake reaction time to the FCW alert). Two promising braking onset models were developed using this "expanded" last-second maneuver database. These models were developed from a database which (combined with Study 1 of Kiefer et al. (1999)) now includes 3,536 last-second braking judgment trials and 790 last-second steering (or lane change) judgment trials.

These models were developed using both linear regression and logistic regression statistical modeling techniques. The former approach predicts a continuous dependent variable, which is then used to decide if the driver is in a hard braking onset scenario. In contrast, the logistic regression approach was used here to predict the probability the driver was in hard braking scenario (and <u>not</u> a normal braking scenario).

The linear regression approach resulted in a model nearly identical to the Required Deceleration Model developed in the first CAMP FCW project (Kiefer et al, 1999). This lack of change in the RDP equation provides validation for the original ("old") equation, and indicates the equation is robust and relatively unaffected by the new Constant ΔV and POV Decelerating-Long Headway Trials which were included in this expanded data set. The logistic regression approach resulted in a new 3-Tiered Inverse TTC-based model, which unlike the Required Deceleration Model, does not require accurate knowledge of lead vehicle deceleration. Instead, the 3-Tiered Inverse TTC model merely requires knowledge of whether or not the lead vehicle is stationary, moving and braking, or moving and not braking. This new model was developed during the process of exploring potential predictors, which looked at "instantaneous" rate of change of the vehicle-to-vehicle kinematic situation (i.e., how fast the kinematic situation was changing). The key component of this model is the inverse (momentary) TTC term, defined as the difference in speed between the lead and following vehicles divided by the range between these two vehicles (or Δ *Velocity / Range*). This 3-Tiered Inverse TTC model can be elegantly described as a model that assumes the driver deceleration response (in response to the crash alert) is based on an inverse TTC threshold that decreases linearly with speed.

These two models were compared on several criteria, which included: predictions under the "nominal" vehicle-to-vehicle kinematic conditions observed in the database, model residuals (the difference between predicted and observed values), estimates of the number of predicted hard braking onsets which were considered (based on certain assumptions) as either "early" or "late", and a domain of validity check which included examining model performance under a range of conditions beyond the scope of the current database. Results showed that the 3-Tiered Inverse Model provided very comparable (and in some cases, more favorable) performance relative to the New Required Deceleration Model. For the 3-Tiered Inverse TTC model, overall, "early" brake onset rates and "late" brake onset rates (using the CAMP Actual Deceleration Parameter Equation Criterion) across the last-second braking database were 4.4% and 4.6%, respectively. The corresponding values for the New Required Deceleration Model were 9.0% and 6.9%, respectively. These results indicate that, overall, the 3-Tiered Inverse TTC Model and the New Required Deceleration Model provided "appropriate" brake onset predictions in 91.0% and 84.1% of the last-second braking trials, respectively. "Appropriate" here refers to avoiding both "early" and "late" brake onset predictions, as they are defined earlier in the paper. A domain of validity check performed with a large range of vehicle-to-vehicle kinematic conditions beyond the current database showed both models behaved very comparably and "sensibly" (e.g., required deceleration values were less than 0.45 g's, with the exception of some extreme kinematic conditions).

The new 3-Tiered Inverse TTC Model has several potential advantages over the New Required Deceleration Model. First, particularly from a near-term FCW system implementation perspective, it is important to stress that this model does not depend on accurate knowledge of lead vehicle deceleration. This is a potential advantage over the Required Deceleration Model since sensing lead vehicle deceleration in an accurate, real-time fashion is technologically challenging. Second, greater flexibility may be allowed by working in the "probability of hard braking" domain, since the designer-selected p-value (or "probability of hard braking" value) inherent to this model can be altered in a very straightforward manner with clear supporting underlying rationale (i.e., changing the p-value changes the probability of hard braking onset the designer is willing to assume). The p-value could be potentially altered to address driver variables (e.g., gender, age), as well as various weather and environmental conditions. In addition, the p-value could potentially be used to provide rationale for graded alerts, for different alert timing settings, and for changing false alarm/miss trade-offs based on kinematic conditions (e.g., during suspected lane-change scenarios, such as under high ΔV conditions). Although FCW alert criterion changes based on the various factors described above certainly can be done with the New Required Deceleration Model, the underlying rationale for such changes and the corresponding magnitude of these changes across kinematic conditions is not as straightforward. In any case, the ability to alter p-values in the 3-Tiered Inverse TTC Model does not imply that determining how/when to alter such p-values is straightforward, merely that a straightforward mechanism exists. Third, whereas the required deceleration approach only used the "hard" last-second braking data directly for modeling purposes, this model uses both the normal and hard braking data, which may help explain why the model performs somewhat better.

This analysis also suggests that the 3-Tiered Inverse TTC Model may better represent the underlying mental process drivers use in deciding when to brake hard (i.e., when they are in their hard versus normal braking envelope). Because the logistic regression approach does not predict a particular kinematic variable (e.g., required deceleration), this approach is not subject to the quirk in linear regression that allows a predictor to also be used in the calculation of the criterion measure. In contrast, the New Required Deceleration Model uses a predictor (e.g., POV deceleration), which is used in calculating the criterion measure (required deceleration). Consequently, although the required deceleration model may perform comparably from a predictive sense, this finding does not necessarily imply that drivers use accurate, real-time lead vehicle deceleration information when making last-second, hard braking decisions. Indeed, the lack of predictive power for the required deceleration measure during logistic regression provides support that such detailed knowledge of lead vehicle deceleration may not be used by driver when making hard braking decisions, and that the 3-Tiered Inverse TTC Model may better represent the underlying process drivers actually use in making these last-second, hard braking decisions. Hence, the 3-Tiered Inverse TTC model may be less "empirically-driven" (i.e., dependent on gathering additional data), and may provide better opportunities for extrapolating beyond the data given the large amount of previous work examining TTC-based measures. (However, it should be cautioned that the vast majority of this automotive-related TTC work is laboratory-based and it unlikely to directly apply to the crash alert timing issues addressed here.)

From a crash alert timing implementation perspective, this suggests that even if accurate knowledge of lead vehicle deceleration is not obtainable, relatively crude lead vehicle deceleration knowledge (such as required by the 3-Tiered Inverse TTC Model) may be adequate for predicting whether or not a driver will perceive they are in their hard versus normal braking envelope. However, it should be stressed that accurate knowledge of lead vehicle deceleration is still desirable for any crash alert timing implementation, since this knowledge can be used to improve predictions associated with calculating the assumed *Delay Time Range*, which along with the assumed *Braking Onset Range*, is used to calculate (total) *Warning Range* (Kiefer et al., 1999). The Delay Time Range is calculated based on the projected change in range to the vehicle ahead during the *Total Delay Time* interval (Kiefer et al., 1999), given prevailing kinematic conditions (i.e., the speed and deceleration levels of the lead and following vehicles). This interval is a composite sum of various system delay times, including the interface delay (i.e., time between the alert criterion violation and crash alert onset), driver brake RT (i.e., time between crash alert onset and driver triggering the brake switch), and brake system delay (i.e., time between driver triggering the brake switch and vehicle slowing).

Further analyses were conducted to investigate the extent to which an alert might be issued prior to an intended "normal" lane-change maneuver, based on brake onset predictions from the Required Deceleration Model and the 3-Tiered Inverse TTC Model. For these models, overall estimates of the incidence of "normal", last-second lane change onsets in the current database occurring closer to the lead vehicle than the predicted (alert-appropriate) braking onsets were slightly higher than 15%. These results suggest that an alert timing approach based only on last-second braking considerations (i.e., an approach which does not consider last-second steering considerations) may result in alerts occurring before the point at which some drivers execute "normal" (albeit last-second) lane change maneuvers.

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

References

Evans, L., and Rothery, R. (1974). *Detection of the Sign of Relative Motion when Following a Vehicle*. Human Factors, 16, 161-173.

Kiefer, R.J., LeBlanc, D., Palmer, M., Salinger, J., Deering, R., and Shulman, M. (1999). *Forward Collision Warning Systems: Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems.* (Report No. DOT-HS-808-964). Washington, DC: Department of Transportation publication.

APPENDIX A

Participant Information Letter

Dear Participant,

You have been asked to participate in research on drivers' steering maneuvers. As a research participant, you will drive a real car at speeds ranging from 30 to 60 mph. During the study, you will be asked to make "last-second" steering judgments in order to pass an artificial car. This "artificial car" is made of a rubber compound and is towed about 40 feet (or one and one half car lengths) behind a real car. After your driving session is finished you will also be asked to complete a questionnaire about your experience.

Safety: If you decide to participate in this study you should know that a number of measures have been taken to insure participants' safety. Even though a collision with the artificial car described above is very unlikely, driving a motor vehicle always involves some risk of an accident. Because of this possibility the artificial car described above was constructed of a "soft" material designed to not cause injury to either your vehicle or its occupants if struck. In addition, the artificial car and towing vehicle are connected with a beam that is designed to collapse and absorb a collision impact. A trained Transportation Research Center test driver will also be a passenger in the car while you are driving. This test driver will have access to passenger-side brakes as an additional safety measure to avoid collisions with the artificial car. At no time will you be asked to perform any unsafe driving actions.

Eligibility: To participate, you must have a minimum of 2 years driving experience and possess a valid, unrestricted (except for corrective eyeglasses) U.S. driver's license. You must be at least 20 years of age. Your hearing and vision must be normal (with correction allowed) and you must be able to drive an automatic transmission vehicle without assistive devices or special equipment. Your participation requires that you must be able to give informed consent. If you are under the influence of alcohol, drugs, or any other substances (e.g., antihistamines) which may impair your ability to drive, you are not eligible for participation. Participants that have used alcohol, drugs, or any other substance which may impair driving ability, within 24 hours prior to their scheduled session will be excluded from participation.

In addition, individuals with a history of brain damage from stroke, tumor, head injury, or infection, epileptic seizures, shortness of breath, chronic respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo or balance problems, diabetes requiring insulin, chronic migraines, tension headaches, or are currently pregnant are not eligible for participation. Individuals who have experienced a recent heart attack or suffer from certain heart conditions may also be ineligible for participation.

Risks: There are some risks and discomforts to which you expose yourself in volunteering for this research. This includes the risk of an accident normally associated with driving, braking, or steering a vehicle in response to a stopped or slowing lead vehicle. However, unlike in normal driving, this lead vehicle will be a "soft" artificial vehicle attached to a collapsible beam and your vehicle's passenger will be a trained Transportation Research Center test driver. This test driver will have access to passenger-side brakes and, if necessary, will override your driving judgments to avoid collisions with the artificial car. If an accident does occur, the experimenters will arrange medical transportation to the nearest medical facility. You will be required to undergo examination by medical personnel. You will be responsible for making arrangements for payment of the expenses of such treatment.

Benefits: There are no direct benefits to you from this research other than payment. However, by participating in this study, you are lending your experience as a driver to research on driver's steering behavior under certain conditions. You will not be informed as to the results of this study.

Payment: You will be paid $150 for participation in this study. The study will take about 2-2 ½ hours. Payment will be made by check at the time of participation.

Withdrawal: Participation in this study is voluntary. You may withdraw at anytime, for any reason, without penalty. Should you withdraw, you will be paid, in full, for any portion of the study you either completed or started.

Confidentiality: The data gathered in this study will be treated with anonymity. Shortly after you have participated, your name will be separated from your data and it will be given a number. Only the Principle Investigator will have access to this coding information. Your name will not appear in any reports or papers written about the project. Any videotapes of the data, which will include video of your head and face, will be kept until they are no longer needed.

The researchers hope that you will agree to participate in this study. If you are willing and are eligible for participation, you should read and sign the Informed Consent Form. The experimenter will require a signed copy of the Informed Consent Form before you can actually participate in the study.

APPENDIX B

Informed Consent

I, ______________________________, agree to participate in research on driver's steering maneuvers.

1. You are being asked to volunteer as a participant in a research project whose purpose and description are contained in the Information Letter: The purpose of this experiment is to investigate driver's steering maneuvers. As a test participant, you will drive a real car at speeds ranging from 30-60 mph. The object you will be driving behind is an "artificial" rear-end of a vehicle made of a rubber compound. This "artificial car" will be towed about 40 feet (or one and one half car lengths) behind a real car. You will be asked to make "last-second" steering judgments in order to pass the artificial car, which will be either stationary or moving. At the conclusion of this study you will be asked to complete a questionnaire about your experience. At no time will you be asked to perform any unsafe driving actions.

The passenger in the car you will be driving will be a trained, Transportation Research Center test driver. The test driver will have access to passenger-side brakes and if necessary, will override your driving judgments to avoid collisions with the artificial car. If you do collide with the artificial car, you should know that it is constructed of a "soft" material such that, if struck, it is designed not to cause injury to either the test participant or researchers. Furthermore, the artificial car and towing vehicle are connected with a beam that is designed to collapse and absorb the collision impact if the artificial car is struck.

2. There are some risks and discomforts to which you expose yourself in volunteering for this research. These include the risk of an accident normally associated with driving a vehicle and responding to a stopped or slowing lead vehicle. However, unlike in normal driving, this lead vehicle will be a "soft" artificial vehicle attached to a collapsible beam (as described above), and your passenger will be a trained test driver. This test driver will have access to passenger-side brakes and if necessary, will override your "last second" driving judgments to avoid collisions with the artificial car.

3. The following precautions will be taken during your drive:

a) The experimenter will always be present in the test vehicle and will monitor your driving. They will ask you to discontinue participation if they feel the risks are too great to continue. However, as long as you are driving the research vehicle, it remains your responsibility to drive in a safe, legal manner.

b) The front seat experimenter will have an override brake pedal.

c) The vehicle is equipped with an airbag and anti-lock brakes. Air bags inflate with great force, faster than the blink of an eye. If you're too close to an inflating air bag, it could seriously injure you. Safety belts help you keep in position before and during a crash. You should always wear your safety belt, even with air bags. You will be required to wear your lap and shoulder belt system during this test anytime the car is on the road. You should sit as far back as possible while still maintaining control of the vehicle.

d) The vehicle is equipped with a fire extinguisher, first-aid kit, and cellular phone.

e) If an accident does occur, the experimenters will arrange medical transportation to the nearest medical facility. You will be required to undergo examination by medical personnel. You will be responsible for making arrangements for payment of the expenses of such treatment.

f) Trained medical personnel will be immediately accessible by phone at all times during testing.

4. The data gathered in this study will be treated with anonymity. Shortly after you have participated, your name will be separated from your data and it will be given a number. Only the Principle Investigator will have access to this coding information. Your name will not appear in any reports or papers written about the project. Any videotapes of your data will be kept until they are no longer needed. It is possible that, should you be involved in an accident during testing, the researchers will have to release your data on your driving in response to a court order.

5. You will be paid $150 for participation in this study. The study will take about 2-2 ½ hours. Payment will be made by check at the time of participation.

6. There are no direct benefits to you from this research other than payment. However, by participating in this study, you are lending your experience and expertise as a driver to investigate driver's steering and braking maneuvers. You will not be informed as to the results of this study.

7. By agreeing to participate, you certify that you possess a valid, unrestricted (except for corrective eye glasses), U.S. drivers license, have a minimum of 2 years driving experience, are 20 years of age or older, have normal hearing and vision (with correction allowed), are able to drive an automatic transmission vehicle without assistive devices or special equipment, are able to give informed consent, and are not under the influence of alcohol, drugs, or any other substances (e.g., antihistamines) which may impair your ability to drive. You also certify that you do not have a history of heart condition or recent heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures in the past 12 months, 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 requiring insulin, chronic migraine or tension headaches, or are pregnant. Additionally, you certify that you have not used alcohol, drugs, or any other substances (e.g., antihistamines) which will impair your ability to drive for a period of no less than 24 hours prior to participation.

8. The experimenters will answer any questions that you might have about this project and you should not sign this informed consent form until you are satisfied that you understand all of the previous descriptions and conditions. You may contact the principal investigator at the following address and telephone number:

Raymond J. Kiefer, Ph.D.
CAMP
Discovery Centre
39255 Country Club Drive
Suite B-30

Farmington Hills, MI 48331
(248) 848-9595 ext. 15

9. If information becomes available which might reasonably be expected to affect my willingness to continue participating in this study, this information will be provided to me.

10. Participation in this study is voluntary. You may withdraw from this study at any time, and for any reason, without penalty. Should you withdraw, you will be paid, in full, for any portion of the study you either completed or started.

11. By signing this form you certify, to the best of your knowledge, that you have no physical ailments or conditions which could either be further aggravated or adversely affected by participation in this study.

I have read and understand the scope of this research program and I have no other questions. I hereby give my consent to participate, but I understand that I may stop at anytime, if I choose to do so.

Participant:

Name:____

Address:____

City, State, Zip:____

Phone:__(_____)__________________________________

Participant Signature:____**Date:**______________

Researcher Signature:______________________________________Date:____________________

APPENDIX C

Participant Screening

Background Information Questionnaire

Before this list of questions is administered, please communicate the following:

"Because of pre-existing health conditions, some people are not eligible for participation in this study. I need to ask you several health-related questions before you can be scheduled for a study session. Your response is voluntary and all responses are confidential. This means that you can refuse to answer any question that you choose and that we will not keep any record of your response. Please answer the following questions:"

1. What is your age?
[Exclude if do not meet age requirements of test.]

2. Gender: male or female

3. Do you currently possess a U.S. drivers license? Are there any restrictions on it? Please bring your drivers license to the study.
[Exclude if don't have a drivers license, if there are any restrictions (day only, to from work, etc.), or cannot produce it.]

4. How many years have you been driving?
[Exclude if less than two years of driving experience.]

5. Are you able to drive an automatic transmission vehicle without assistive devices or special equipment?
[Exclude if no.]

6. Your hearing and vision will be tested. Do you use any corrective devices for either? Are you using them now? Please bring the corrective devices you use with you to the study.
[Exclude if cannot meet criteria for either test.]

7. Are you currently taking any drugs or substances (e.g., antihistamines) that may impair your ability to drive? If yes, please explain.
[Exclude if answer is yes]

8.* Do you suffer from a heart condition such as disturbance of the hearth rhythm or the experience of a heart attack? If yes, please describe.
[Exclude if there has been a heart attack in the past 6 months, or if there is a history of ventricular flutter or fibrillation, or asystole requiring cardioversion. Potential participants with atrial fibrillation may be acceptable, given that their hearth rhythm is now stable following medical treatment or pacemaker implants.]

9. * Have you ever suffered brain damage from a stroke, tumor, head injury, or infection? If yes, what are the resulting effects? Do you have visual loss, blurring, or double vision; weakness, numbness, or funny feelings in the arms, legs, or face; trouble swallowing; slurred speech; uncoordination or loss of control; trouble walking, trouble thinking, remembering, talking, or understanding?
[Exclude if there has been a stroke within the past 3 months, there is an active tumor, or if there are lingering effects or transient ischemic attack in the past year.]

10. * Have you ever been diagnosed with a serious or terminal illness? If yes, is the condition still active? Are there any lingering effects? If yes, do you care to describe?
[Exclude if there is any current serious illness.]

11. * Have you ever been diagnosed with seizures or epilepsy? If yes, how frequently and what type?
[Exclude if there has been a seizure in the past 12 months.]

12. * Do you suffer from a respiratory disorder such as asthma or chronic bronchitis? If yes, please describe.
[Exclude if disorder results in obvious or continuous shortness of breath or if the subject requires chronic medical therapy such as theophyllin, inhalers, steroid medications, and especially oxygen therapy.]

13. * Do you ever suffer from motion sickness? If yes, on what mode of transportation and what were the conditions (e.g., rough sea, back seat, etc.)? What symptoms did you experience? How old were you when this occurred?
[Exclude if sickness occurs often, occurs in mild to moderate conditions, or results in severe symptoms.]

14. * Do you suffer from inner ear, dizziness, vertigo, or balance problems? If yes, please describe. Do you have Meniere's disease?
[Exclude if there has been any history of inner ear, dizziness, vertigo, or balance problem within the past 12 months.]

15. * Do you have Diabetes? Have you ever been diagnosed with hypoglycemia? If yes, do you take insulin or any other medication for blood sugar?
[Exclude if insulin is taken for this condition.]

16. * Do you have migraine or tension headaches? If yes, what is the nature of this pain? How often and when was the last headache? Are you currently taking medication for these headaches? If so, what are you taking?
[Exclude if headaches occur greater than 2 times a month, if there has been a headache in the past 48 hours, or if the subject takes chronic daily or narcotic medications.]

17. * Are you currently taking any medication? If yes, what is the medication and what is it for?
[Exclude if medication is for motion sickness, or any of the conditions mentioned above that indicates a problem mentioned above that may have been inadvertently or otherwise denied previously.]

18. * Are you, or is there a possibility that you are pregnant?
[Exclude if there is any possibility of pregnancy.]

19.* Have you ever been diagnosed with a mood problem or a psychiatric disorder? If yes, are you taking medication? Please describe.
[Exclude for specific disorders, including schizophrenia, abuse/dependency on psychoactive or illicit drugs, anxiety attacks, or claustrophobia]

If a volunteer is...	**and...**	**Proceed by...**
Eligible	NA	Scheduling a study session.
Not Eligible	Exclusion is TEMPORARY	Saying "I am not able to schedule you at this time, however, if you are interested you can volunteer again when _____(fill in restriction, e.g., you are not pregnant). We will be glad to reconsider you in a study at that time. We appreciate your interest and hope to hear from you in the future."
Not Eligible	Exclusion is PERMANENT	"I am not able to schedule you for this study because of ____ (i.e., susceptibility to motion sickness). Understand that we do this with your best interest in mind. We appreciate you willingness of volunteer."

*(Adapted from the University of Iowa "Participant Exclusion Criteria")

APPENDIX D

Preliminary Last-Second Steering Model

Model Development

Due to the relatively limited number of steering (relative to braking) trials conducted, and the more limited number of different vehicle-to-vehicle kinematic conditions examined during steering relative to braking trials (see Figure 2), only limited attempts were made to model the steering data. The preliminary steering model developed was based on 790 last-second steering trials conducted at the Transportation Research Center in East Liberty, Ohio. The steering database contains approximately 72 data points for each of the 11 vehicle-to-vehicle kinematic conditions evaluated, though not all subjects were tested in all conditions. For each kinematic condition, subjects were tested under both “normal” last-second steering and “hard” last-second steering conditions.

In the modeling process, each observation was treated as independent (as was the case with the last-second braking data), even though each driver provided several observations. Overall, these limited modeling attempts tended to suggest a last-second steering model that was more consistent with an inverse TTC-based model rather than a required deceleration-based model.

As with the modeling of the last-second braking data, logistic regression was used to predict the probability of “hard” steering onset (and not “normal” steering onset) given a specific vehicle-to-vehicle kinematic scenario. That is, the binary outcome was whether or not a specific vehicle-to-vehicle kinematic steering onset scenario was a “normal”, last-second steering onset scenario or a “hard”, last-second steering onset scenario. Both the “normal” and “hard” last-second steering data were used directly in statistical modeling process. This logistic regression approaches utilized the following “raw” data available at last-second steering onset: following driver (SV) speed, lead vehicle (POV) speed, following driver (SV) acceleration, lead vehicle (POV) acceleration (real-time, no delay), and the range between the following driver’s vehicle and the vehicle ahead.

Numerous transformations of these variables, including required deceleration, TTC-Case 1, TTC-Case 2, ΔV, and ΔV-squared were used as potential predictors. The data were also divided into three types (based on approach scenario): POV Decelerating Trials, Constant ΔV Trials, and POV Stationary Trials. The resulting best-fit model as does not distinguish among these three types of trials above (i.e., using a separate slope and intercept for the three types of trials did not improve model fit). The probability of “hard” steering onset was a function only of inverse TTC-Case 1 (or inverse momentary TTC), as shown in the equation below:

$$p = \frac{1}{1 + e^{(-3.148 + 11.372(1/m))}}$$

where,

p is the probability of a “hard” steering onset
m is momentary time to collision (i.e., range / ΔV)

This is subsequently referred to as the “*Steering Inverse TTC Model*”.

Model Performance

The performance of the Steering Inverse TTC Model was assessed in two different ways. First, required deceleration, TTC-Case 2, and range values at predicted alert onset were compared to the corresponding observed values for those measures. More specifically, residuals were calculated by subtracting predicted values from observed values. Hence, for each measure, positive values indicates predictions that were, on average, late, and negative values indicate predictions that were, on average, early. Similar to the last-second braking data modeling, the probability cutoff value of 0.75 was chosen to define the criterion for "hard" steering onset. (Note that choosing a p=0.75 value corresponds loosely to choosing a p=0.50 value for the last-second "hard" steering data set only). Table 1 provides the mean required deceleration, TTC-Case 2, and range residuals for each kinematic condition examined.

Table 1. Mean Required Deceleration, TTC-Case 2, and Range Residuals (Observed minus Predicted Values) for Steering Inverse TTC Model (p=0.75)

	Mean Residuals		
Kinematic Conditions SV speed (mph)/POV speed (mph)/POV decel. (g)	Required Deceleration (g)	TTC-Case 2 (sec)	Range (feet)
30/30/-.15	0.03	0.75	21
30/30/-.39	0.08	0.64	25
60/60/-.15	0.04	0.93	38
60/60/-.39	0.10	0.82	54
30/20/0	0.01	0.61	10
30/10/0	-0.01	0.05	2
60/50/0	0.01	1.32	17
60/30/0	0.01	0.33	16
60/15/0	0.00	0.22	16
30/0/0	-0.01	-0.03	0
60/0/0	0.03	0.29	26

A second way of evaluating the performance of the Steering Inverse TTC Model is shown in Table 2 and Table 3. Nominal conditions and corresponding Steering Inverse TTC Model predictions are shown in Table 2. These nominal conditions were based on the average kinematic descriptors for the 11 vehicle-to-vehicle kinematic conditions examined. Table 3 gives the observed mean range and mean required deceleration values at "hard" steering onset. Figure 1 provides a direct comparison of the predicted steering onsets relative to the observed mean "hard" last-second steering onsets using the required deceleration measure. Although these observed values provide a benchmark from which to compare the extent to which the model results match observed values, strictly speaking, it should be noted that these observed values come from a wide range of initial vehicle-to-vehicle kinematic conditions, whereas the model predictions come from one specific nominal condition.

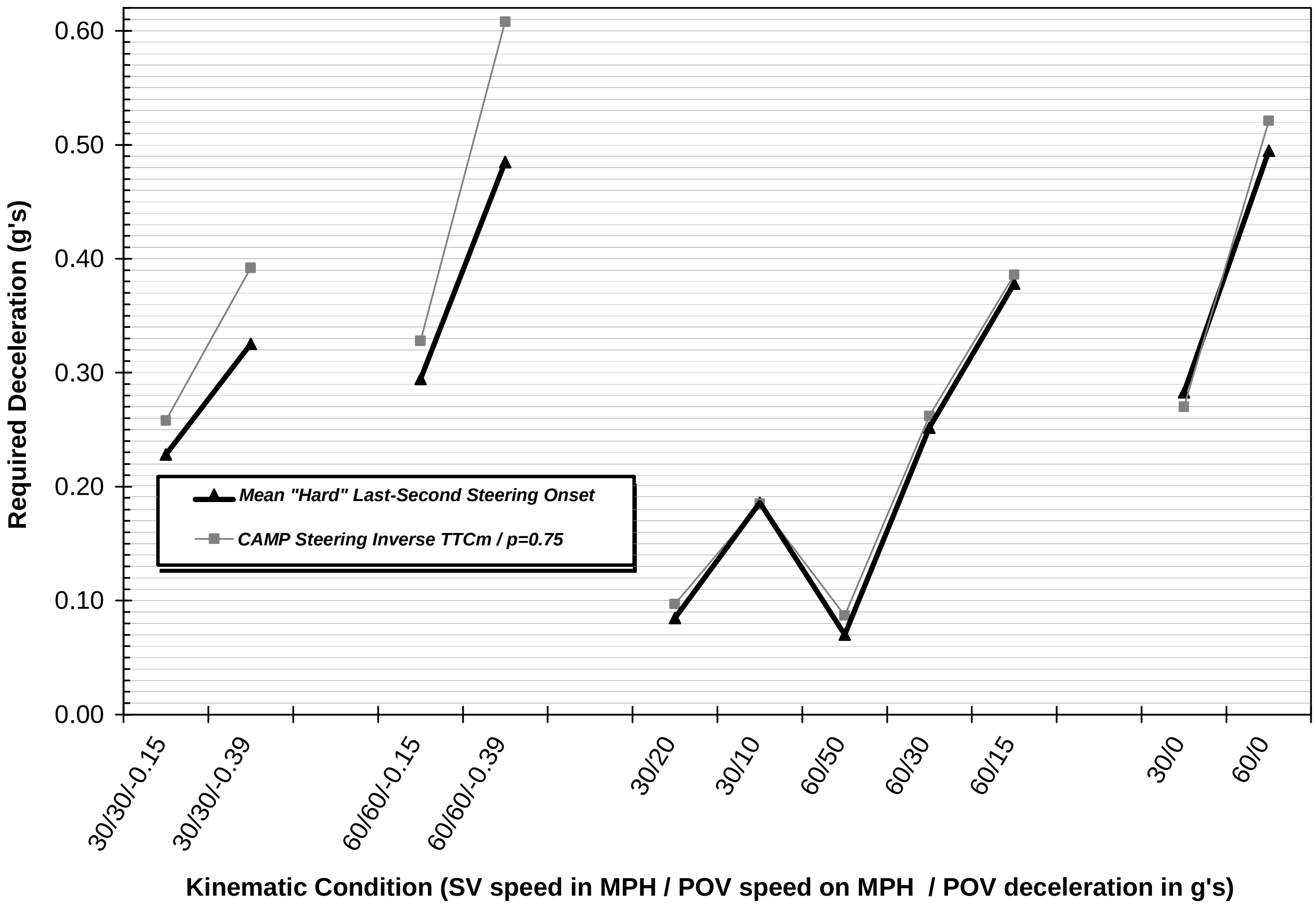
<u>Table 2</u>. Definitions of 11 "Nominal" Vehicle-to-Vehicle Kinematic Conditions and Steering Inverse TTC Model (p=0.75) Predictions for the Range and Required Deceleration at "Hard" Steering Onset for these Nominal Conditions

Kinematic Condition SV speed (mph)/POV speed (mph)/POV decel. (g)	SV Speed (mph)	POV Speed (mph)	ΔV (mph)	POV Decel. (g)	Predicted Range (feet)	Predicted Required Deceleration (g)
30/30/-.15	30	19.8	12.8	-0.15	50	-0.26
30/30/-.39	30	17.2	13.8	-0.39	54	-0.39
60/60/-.15	60	46.0	20.9	-0.15	82	-0.33
60/60/-.39	60	41.5	28.0	-0.39	110	-0.61
30/20/0	30	19.5	11.4	0	45	-0.10
30/10/0	30	9.6	21.8	0	86	-0.19
60/50/0	60	50.6	10.2	0	40	-0.09
60/30/0	60	31.3	30.8	0	121	-0.26
60/15/0	60	15.6	45.4	0	178	-0.39
30/0/0	30	0.1	31.7	0	125	-0.27
60/0/0	60	0.9	61.3	0	241	-0.52

<u>Table 3</u>. Mean Observed Range and Required Deceleration at "Hard" Steering Onset for Each Kinematic Condition

Kinematic Condition SV speed (mph)/POV speed (mph)/POV decel. (g)	Mean Range Observed (feet)	Mean Required Decel. Observed (g)
30/30/-.15	71	-0.22
30/30/-.39	80	-0.32
60/60/-.15	120	-0.30
60/60/-.39	164	-0.49
30/20/0	55	-0.09
30/10/0	87	-0.19
60/50/0	57	-0.07
60/30/0	137	-0.25
60/15/0	194	-0.38
30/0/0	124	-0.28
60/0/0	266	-0.50

<u>Figure 1</u>. Required Deceleration at Steering Onset Predictions fro Steering Model under NominalConditions (as well as the Mean "Hard" Required Decelerations at Last-Second Steering Onset) for Each Kinematic Condition



Based on these limited results, it appears that the Steering Inverse TTC Model produces relatively good predictions for the Constant ΔV Trials and POV Stationary Trials. However, the predictions appear late for the POV Decelerating Trials evaluated, particularly when the lead vehicle is decelerating at the highest level evaluated. This preliminary last-second steering model should be refined and updated as a richer set of data and information becomes available.

APPENDIX E

Psuedo-Code to Implement the 3-Tiered Inverse Time-To-Collision Model

This pseudo-code is intended to guide implementation of an FCW crash alert timing algorithm that uses the CAMP "logistic function fit" model (also called the "inverse TTC braking model"). This model is based on data collected in two sets of closed-course human factors tests. The particular model addressed here is a "3-tier" model in which separate model fits have been made to three subsets of the human factors data:

- approaches at constant speed to a stationary target,
- approaches at constant speed to a moving target whose speed is also constant, and
- approaches at constant speed to a decelerating target –these trials involve an initial condition of constant-speed following, with the preceding vehicle then beginning a braking maneuver.

This CAMP model affects only a portion of the crash alert timing algorithm – the calculation of the range needed to avoid an impact once the driver begins braking, based on vehicle speeds and, optionally, any acceleration estimates that are available. The code below also includes a term to account for driver reaction time and system delays, as well as additional logic so that the range computation is only used at appropriate sets of speeds.

Additional logic should be wrapped around the material presented here so that an acceptable alert algorithm results (e.g., "Don't warn if the driver is on the brakes," "Don't warn if the host vehicle speed is too low", etc.) This memo addresses only the timing of alerts and assumes that other measurements and logic are used to identify which other vehicles on the roadway are potential "targets" for possible FCW alerts.

This psuedo-code was written for this memo, and has not been tested in a vehicle.

<u>Pseudo-code</u>

```
Data types

All variables are floating point variables (VL, VF, aF, aL, Rmeas, Ra, VFmin,
VLstopped, DT, VFp, VLp, DTR, BOR, a, b, c, astat, bstat, amove, bmove,
adecel, bdecel, P, L, aLtrans1, aLtrans2, trans_ratio,)

Measurement variables assumed (Accelerations can be approximate and/or
filtered values)

VF;    Comment:  following veh spd, meters/sec

VL;    Comment:  lead veh spd, meters/sec

aF;    Comment:  following veh accel (negative for brkg), m/s/s

aL;    Comment:  lead veh accel (negative for brkg), m/s/s

Rmeas; Comment:  measured range (meters)
```

Comment: Outputs

Ra;   Comment: range threshold that determines whether the imminent-level alert is given (meters)

Model parameters:

Model parameters for the case when the lead vehicle is stationary:

astat = 9.073, bstat = -24.225; Comment: unitless parameters

For the case when the lead vehicle is moving at constant speed:

amove = 6.092, bmove = -12.584; Comment: unitless parameters

For the case when the lead vehicle is moving and braking:

adecel = 6.092, bdecel = -18.816; Comment: unitless parameters

For all cases:

c = -0.1195; Comment: for speeds in m/s

Comment: Parameters (specific values below are "placeholder" values based on engineering judgment – the values used are not critical to the algorithm)

VFmin = 4.47; Comment: Min host vehicle speed at which an FCW alert is allowed, m/s (10 mph)

VLstopped = 2.23; Comment: The model's "POV-stopped" case is applied when the POV speed is below this value, m/sec (5 mph). Figure 1 shows that this logic is applied at all host vehicle speeds.

Comment: TUNING VARIABLES:

DT = 1.18 + 0.20 + interface delay; Comment: DT = delay time (sec) used in alert range calculation. 1.18 is driver RT, 0.20 sec for brake, interface delay is time needed to present display
P = 0.75;   Comment: logistic fn tuning parameter (likely_values between .7 and .95)

aLtrans1 = -0.49 (m/s/s); Comment: a smooth transition is made between the two cases in which the POV is moving by interpolating the 'a' and 'b' model parameter values at lead vehicle acceleration levels between the aLtrans1 and aLtrans2 values (see Figure 1). When the lead vehicle acceleration estimate is above aLtrans1 the algorithm applies the "POV moving but not braking" case. (-0.49 m/s/s is –0.05g)

aLtrans2 = -0.98 (m/s/s); Comment: see aLtrans1 comment. When the lead vehicle acceleration is below this value (i.e., has a higher braking value), the algorithm applies the "POV moving and braking" case. (-0.98 m/s/s = -0.10g)

Comment: Handle stopped vehs

Comment: Assume that oncoming traffic is not even reported to this routine.
Comment: Do not allow lead vehicle to accelerate from a stop (noise issue).

```
If (VL < 0),

      VL = 0;

      aL = 0;

Endif
```

Comment: Compute expected speeds after the delay time passes

```
VFp = VF + aF*DT;

VLp = VL + aL*DT;

If VFp < 0, VFp = 0, Endif

If VLp < 0, VLp = 0, Endif
```

Comment: Some speed conditions result in no alert

```
If (VF < VFmin)  OR (VFp < VLp),

7     Ra = 0;

      EXIT routine   Comment:  No alert in these speed conditions

Endif
```

Comment: Compute the "delay time range" – the amt of range consumed during the total delays (driver + system)

```
If (VLp > 0),

      DTR = (VF – VL)*DT + 1/2 * (aF – aL) DT*DT;

Elseif (VLp = 0),

      DTR = VF*DT + ½ * aF * DT*DT;

      If (VL > 0),   comment: lead veh stops during DT

            DTR = DTR + VL*VL/2.0/aL;

      Endif

Endif
```

Comment: Compute the brake onset range (m)

```
If (VL < VLstopped),

      a = astat, b = bstat;

Else

      If aL > aLtrans1,

            a = amove, b = bmove;

      Else if (aL < aLtrans2),

            a = adecel, b = bdecel;

      Else  Comment: transition between the two POV-moving cases

            trans_ratio = (aL - aLtrans2)/(aLtrans1 - aLtrans2);

            b = bdecel + trans_ratio*(bmove - bdecel);

            a = adecel + trans_ratio*(amove - adecel);

      End if

Endif

L = log(1/P - 1);   Comment: natural log

BOR = b*(VFp - VLp)/(L-a-c*VFp);
```

Comment: Compute range threshold for issuing imminent stage alert. Issue alert if appropriate

```
Ra = DTR + BOR;

If (Rmeas < Ra),

      Issue imminent-stage alert.

Else

      Do not issue imminent-stage alert.

Endif
```

<u>End of psuedo code</u>

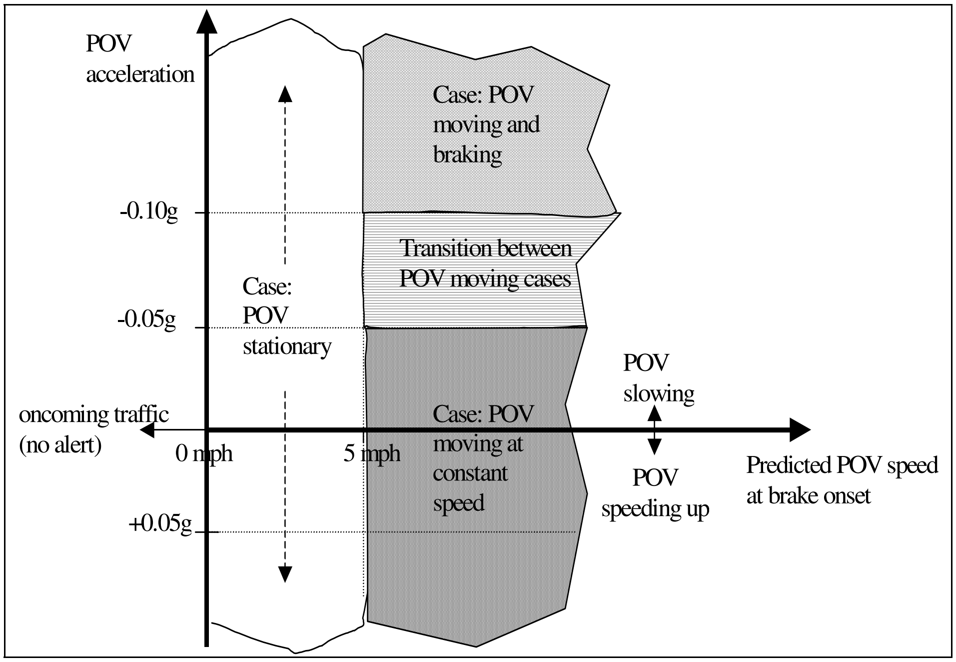


Figure 1: Diagram showing the boundaries between the three cases of the 3-tier inverse TTC model

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