<2001-01-0463>

A New Paradigm for Rear-end Crash Prevention Driving Performance

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ABSTRACT

This paper presents a new data analysis approach to describe driver performance in situations that have the potential of leading to a rear-end crash. The approach provides at least two key benefits. It provides a unified means of analyzing data from different sources such as simulators, test tracks, and instrumented vehicles. It may also provide a means of addressing the huge diversity of driver performance in pre-crash situations.

INTRODUCTION

This paper presents a new approach to analysis of data which describes driver performance in situations that often result in rear-end crashes. The analysis introduces the concept of a crash prevention boundary -- a theoretical, deterministic avoidance threshold that relates driver reaction to the dynamics between two vehicles in an impending crash. The crash prevention boundary provides two key benefits. It allows a unified means of analyzing data from different sources such as driving simulators, recorded naturalistic driving incidents, and controlled test track driving scenarios. It also provides a means of addressing the diversity of driver performance during the pre-crash situation.

The paper consists of a short review of past studies that sought to define driving conditions and driver behavior leading to rear-end crashes. Many of the studies also examined the modification of driver behavior by using a warning system to prevent crashes or mitigate crash severity. The review of previous work is followed by the definition of a deterministic relationship – a crash prevention boundary (CPB) – which becomes the framework for making comparisons of driver braking responses for different driving conditions. Driver response data from tests on the Iowa Driving Simulator are then presented in the CPB framework. The authors believe that this approach can be used to expand on previously published analysis of these experimental results. Analysis of these data demonstrates how the CPB can then be extended and applied to additional sets of similar driving data.

BACKGROUND

Recent data shows that drivers in the United States accumulate a total of more that 2.6 trillion miles of travel annually [1]. These same drivers experience more than 1.8 million crashes annually where one vehicle collides with the rear of another [2]. Thus, there is approximately one rear-end crash for every two million vehicle-miles of travel each year. Also, one study has found that any particular driver brakes about 50,000 times each year [3]. Most of these brake applications occur in routine stops and adjustments of speed in traffic; but each event has the potential to be a crash if the driver does not brake. This suggests that nationally, there are more than 10 trillion brake applications each year. Many of these, even if there is a relatively low level of deceleration, serve the purpose of preventing a collision. This leads to the question that underlies this paper, as well as a large body of other research; "What is different during those 1.8 million events were the driver could not, or did not, prevent a rear-end collision than during the other 10 trillion times that drivers braked and prevented a crash?"

A number of studies of rear-end crash dynamics examined the basis for warning drivers of potential rear-end crashes. Examples of such efforts from 1997 – 2000 include the following National Highway Transportation Safety Agency (NHTSA) contracts: Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS); Sensor Technologies & Systems analysis of rear-end warning system performance; Intelligent Cruise Control (ICC) Field Operational Test Evaluation; the Crash Avoidance Metrics Partnership (CAMP); University of Iowa Driving Simulator (IDS) Tests; and the Johns Hopkins University Applied Physics Laboratory (JHU/APL) Rear-end Collision Symposium. A synopsis of each is given below.

The goal of the FOCAS work [4] was to advance the development of sensors and systems for commercial use in assisting the forward crash-avoidance performance of drivers. To aid in progressing towards this goal, the program created tools, methodologies, and knowledge-bases to expedite the development of adaptive cruise control (ACC) systems as well as systems providing forward collision warning (FCW) alerts. The results, findings, and conclusions of the program are numerous. The program was evolutionary both in terms of hardware and software advancements and more importantly understanding the driver's role in the application of this new technology. Prototype systems were used by lay persons in naturalistic driving. The culmination of the project resulted in progress in five subject areas: (1) evaluation of ACC-with braking, (2) braking latency, (3) development of a NHTSA warning algorithm, (4) evaluation of three FCW algorithms, and (5) research of vigilance as it relates to deceleration authority of an ACC system. The ACC systems developed in this study were well liked by drivers, convenient to use, and did not present any clear safety concerns.

Sensor Technologies & Systems, formerly Frontier Engineering Sciences, Inc. [5], studied the improvement on driver behavior of a rear-end warning system as well as the effect of choice of headway values on the effectiveness of the warning system. Using the Iowa Driving Simulator, data was collected with and without the warning system for various driving conditions. This study concluded that a warning system is useful for shortest headway conditions tested and that drivers may be distracted or confused by collision warning information that is presented too early (nuisance alarm).

The ICC Field Operational Test Evaluation [6] collected data using instrumented vehicles with and without ACC. Prevailing tendencies of drivers in the choice of headway values as well as driving habits were studied. It was concluded that the ACC system that was tested provided a safety benefit for drivers.

In a study conducted by the Crash Avoidance Metrics Partnership [7] a series of controlled experiments were carried out on test tracks to determine driver response to several collision warning alert algorithms as part of an overall study to develop objective test procedures for rear-end collision warning systems. Useful data for driver braking behavior and response time were derived from this study.

The University of Iowa [8] studied the effect of a rear-end warning system on a distracted driver for varying driving conditions and settings for the warning system assumptions. It was concluded that the warning system that was tested reduces the chance of collision and that an early warning provided a greater benefit than a late warning.

NHTSA sponsored the APL symposium [9] that brought together a wide representation from industry and government on the subject of rear-end collision avoidance and ICC. Information was shared in presentations to promote synergism within the entire community of interested parties.

EFFECTIVENESS OF A CRASH WARNING SYSTEM

Each of the studies noted above has addressed specific aspects of rear-end crash avoidance analysis. Some of the studies addressed performance specifications, some addressed effectiveness of crash warning systems, some are based on naturalistic driving, while others included tests in driving simulators or on test tracks. A review of these studies points out that there is no common analytical framework for comparing results. The work described in this paper is a first step toward development of such a framework.

A complete framework would cover all types of crashes and all subsets of each type. The framework developed in this paper is focused on the family of rear-end crashes that result from situations where two vehicles, that are initially traveling at the same speed, begin to close on each other due to deceleration of the lead-vehicle. At some point, the lead-vehicle will brake resulting in braking by the following-vehicle. The initial dynamic conditions of such a situation as well as the driver responses will lead to some crashes and some crash avoidances (no crashes). Proper countermeasures will help avoid many would-be crashes and lead to safer highways.

REAR-END CRASH DYNAMICS

Figure 1 illustrates a situation where two vehicles are initially traveling without any significant conflict. A driving conflict arises because the lead-vehicle brakes. The time at which the lead-vehicle begins to brake is used as a primary reference and is defined as $t = 0$. Also, the location of the front of the following-vehicle at $t = 0$ is defined to be zero distance. The driver of the following-vehicle notices the conflict due to brake lights, the perceived closing rate, other cues, or a warning at time, $t = t_w$. The driver then takes action at time, $t = t_b$ resulting in a total crash avoidance, a near crash, or a crash. If action is taken quickly enough with sufficient braking and/or steering, then a crash is avoided and the vehicles have a point of closest approach at $t = t_s$. If the driver is occupied or distracted with another task when the driving conflict arises, then a crash is more likely.

SCENARIO DEFINITION

The starting point (initial conditions) for this scenario definition is the time when the lead-vehicle begins to decelerate. Prior to this point, the two vehicles are traveling at a constant separation with no closing rate. After the starting point the vehicles are closing due to lead-vehicle deceleration.

Thus, the initial conditions at the starting point for this family of rear-end crash situations are the traveling speed (where both vehicles are initially traveling at the same speed), the initial separation between the two vehicles, and the level of deceleration of the lead-vehicle. Initial speed, V_o, and separation distance, R_o, may be combined to provide the value of headway, T_h. Headway is the amount of time it takes the following-vehicle to cover the distance, R_o, when traveling at speed V_o. The significance of headway is in its relationship to the response time of the following-vehicle driver. If the following-vehicle driver's brake response time is equal to the value of the initial headway and the following-vehicle driver applies the same deceleration profile as the lead-vehicle experiences, the two vehicles will come to a stop without a collision but will be bumper-to-bumper at the end of the event. If the following-driver responds more quickly, less braking is required; and if the following-driver responds less quickly, more braking is required to avoid a crash.

In such scenarios, the following-vehicle driver should notice the brake lights, higher closing rate, or other cues and react to them as the danger of a crash is perceived. The reaction should be to brake hard enough to slow or stop before a crash.

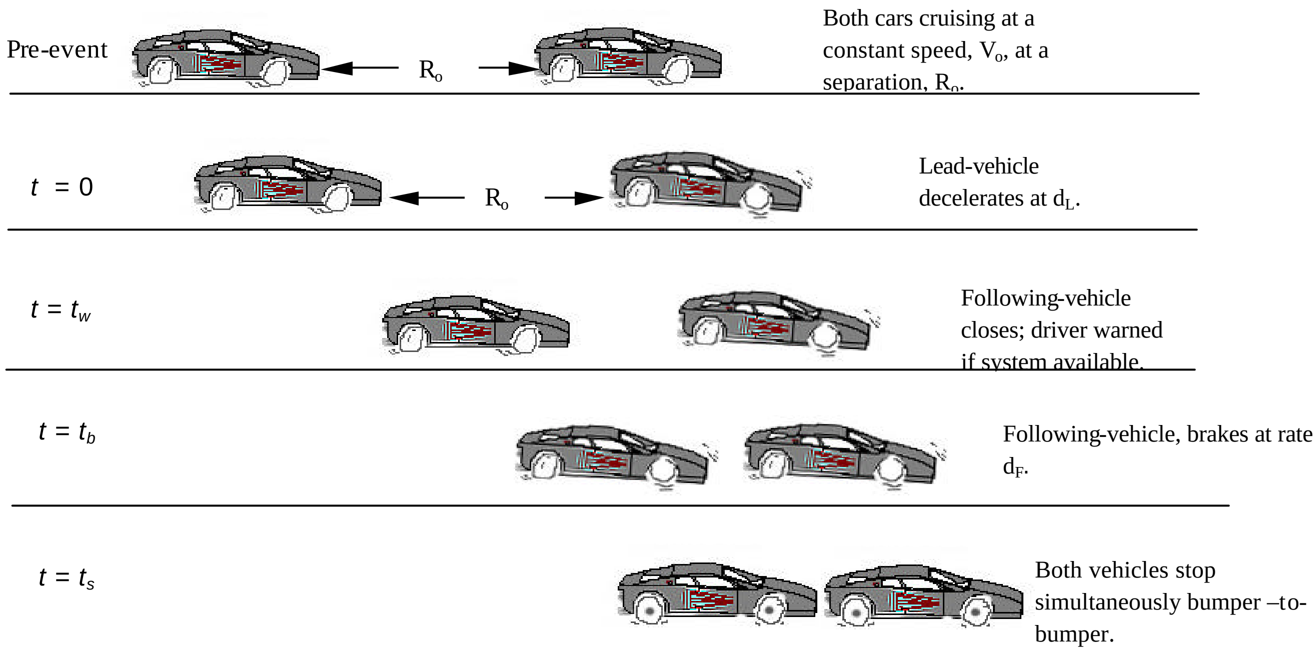

Figure 1 Typical Rear-end Driving Scenario

If the driver is distracted or does not perceive the lead-vehicle deceleration, an imminent crash warning can be given. Descriptions of algorithms for providing such a warning have been described in the literature [7, 11]. Assuming that only braking occurred, the two key variables that describe the following-vehicle driver's crash prevention response are:

1. t_b, the brake response time of the following-vehicle driver relative to the initial braking by the lead-vehicle, and
2. d_F, the level of deceleration of the following-vehicle.

The <u>brake response time</u>, t_b, is defined as the time span from start of lead-vehicle deceleration (initial conditions/starting point) until the initiation of braking by the driver of the following vehicle. The <u>level of deceleration</u>, d_F, of the following-vehicle is defined as the average deceleration over the time from the start of following-vehicle deceleration (braking) until the following-vehicle stops.

THE CRASH PREVENTION BOUNDARY

The underlying idea behind the analytical framework of a crash prevention boundary (CPB) is that for any given set of initial dynamic conditions, there is a subset of values of driver brake response time, t_b, and level of deceleration, d_F, which will result in crash avoidance. The corollary is that there is also a subset of values of these two variables that produce a crash. The CPB is a deterministic relationship that separates these two subsets of possibilities.

Thus, the CPB is an analytically derived expression that separates driver response values into those that provide crash avoidance and those that result in crashes. The CPB expression describes the limiting case between the two variables t_b and d_F. If a driver's brake response time and deceleration satisfy the relationship, the two vehicles will have zero closing speed at the point of closest approach. Also, the point of closest approach will also be at zero range (i.e., the bumpers will be touching). The desired deterministic relationship for the CPB is a combination of logic criteria and algebraic relationships as shown in equations 1 and 2. The detailed development is provided in Appendix A.

$$t_b = R_0/V_0 + (V_0)[1/d_L - 1/d_F]/2 \qquad \text{if } d_F < d_F^* \qquad (1)$$

$$t_b = [(2V_0T_h)(1 - d_L/d_F)/d_L]^{1/2} \qquad \text{if } d_F > d_F^* \qquad (2)$$

where crossover deceleration, $d_F^* = d_L V_0^2/(V_0^2 - 2d_L R_0)$ (See Section A.1).

Both of the above equations assume that the lead-vehicle comes to a stop. In equation (1) the lead-vehicle and the following-vehicle are stopped at the point of closest approach. Equation (2) reflects the situation where both vehicles are moving at the point of closest approach. The value of crossover deceleration, d_F^*, is the separating criteria for these two situations. The derivation of the expression for following-vehicle crossover deceleration is given in Appendix A.1. Expressions (1) and (2) can be combined with expressions for the time-to-collision (TTC) at the beginning of the event to provide simplified expressions for the CPB. The expressions for time-to-collision are:

$$TTC = TTC1 = T_h + V_0/(2\, d_L) \quad \text{if} \quad d_L > d_L^*, \qquad (3)$$

and

$$TTC = TTC2 = (2V_0T_h/d_L)^{1/2} \quad \text{if} \quad d_L < d_L^* \qquad (4)$$

where $d_L^* = V_0/(2T_h)$ and $T_h = R_0/V_0$ (See Section A.4).

Then, the CPB may be expressed in terms of TTC1 and TTC2,

$$t_b = TTC1 - V_0/(2d_F), \quad \text{if} \;\; d_F < d_F^* \qquad (5)$$
$$t_b = TTC2(1 - d_L/d_F)^{1/2} \;\; \text{if} \;\; d_F > d_F^* \qquad (6)$$

Thus, the relationships (1) and (2) or (5) and (6) between t_b and d_F describe the Crash Prevention Boundary (CPB). Based on the equations given above and given a set of initial conditions of R_0, V_0, and d_L a CPB can be computed and plotted as shown in Figure 2. The value of TTC is also shown on this figure. It can be seen from equations 5 and 6 that the CPB is asymptotic to TTC. The following-vehicle driver's response is described by the point, (d_F, t_b). Braking at sufficient average level within the required time prevents a collision and plots below the CPB, while lighter braking with a greater delay will lead to a collision and plots above the CPB. Doing nothing after the initiation of the conflict will cause a collision at TTC.

APPLICATION

As an example of the application of the CPB approach, data from an experiment [10] using a driving simulator are presented in this format. The purpose of the experiment was to investigate how distracted drivers respond to imminent rear-end collision situations – both with a warning and without a warning. The experiment examined how variations in warning algorithm parameters affect the ability of a warning to aid distracted drivers. The derivation of this algorithm is described in [11].

Four sets of initial conditions were used in this experiment. Initial conditions included velocities of 35 and 55 mph, initial headway was either 1.7 or 2.5 seconds, and lead-vehicle decelerations were 0.40 and 0.55 g. Within each set of initial conditions, testing was performed using subjects with no warning (baseline), subjects aided by a short warning, and subjects aided by a long warning. In this context, long and short are used relative to the start of the driving scenario. Short warnings were based on the assumption that the following-vehicle driver would brake after a delay of 1.5 seconds after the warning at an average of 0.4g. Long warnings were based on the assumption that the driver would brake after 1.5 seconds at 0.75g. Long and short warning set points are also shown in Figure 2 to illustrate the relationship between the CPB and warning criteria used in this group of tests. In general, the "long" warnings occurred about 1 second later than the "short" warnings. Comparisons were made within each set between the baseline and short warning as well as comparison of baseline with long warning results. Drivers were distracted with a visually demanding number reading task. The simulator allowed drivers to follow a course, deliberately be distracted, observe a braking vehicle, and respond to the crash threat in a naturalistic way.

All test conditions are summarized in Table 1. Twenty subjects were tested for each of the 12 test conditions for a total of 240 tests in this experiment. The baseline driver performance data for one of the test conditions (IDS Test Condition 1) are shown in Figure 3. In this test, two of the 20 drivers chose to steer rather than brake. Thus, there are 18 subjects included in this analysis. Of these, 11 braked in a manner that avoided a crash while the performance of 7 was not sufficient to avoid a crash. Note that the same initial conditions are used as in the example collision prevention boundary of Figure 2. If Figures 2 and 3 are superimposed, the result is shown in Figure 4. This figure demonstrates a rather remarkable feature of the CPB analytical framework. Drivers who performed in a way that was predicted by the CPB to result in a crash, i.e. points above the line, did indeed experience a crash on the simulator. Conversely, drivers who performed in a way that the CPB predicted would avoid a crash did indeed avoid a crash, i.e. points below the line, on the simulator.

Initial Condition Set	Test Condition	Vo(mph)	d_L(g's)	T_h(sec)	Warning Algorithm dF(g's) Design Point	Warning
1	1	35	0.4	1.7	None	Baseline
	2	35	0.4	1.7	0.40	Short
	3	35	0.4	1.7	0.75	Long
2	4	35	0.55	2.5	None	Baseline
	5	35	0.55	2.5	0.40	Short
	6	35	0.55	2.5	0.75	Long
3	7	55	0.4	1.7	None	Baseline
	8	55	0.4	1.7	0.40	Short
	9	55	0.4	1.7	0.75	Long
4	10	55	0.55	2.5	None	Baseline
	11	55	0.55	2.5	0.40	Short
	12	55	0.55	2.5	0.75	Long

Table 1. IDS Test Design

The complete set of results from the driving simulator experiment are included in Appendix B. Each figure of Appendix B contains the data from a baseline condition in addition to a condition where there was a warning. Each figure also includes two other features. One is the crash prevention boundary that corresponds to the initial conditions for the particular IDS test condition. The other is a marker that identifies the set-point (assumed reaction time of a driver to the warning and level of deceleration) of the warning algorithm.

OBSERVATIONS

Perhaps the most noticeable result of comparing the experimental data with the corresponding CPBs is the additional insight that can be gained by having a graphical tool for quickly comparing experimental results with theoretical predictions. The CPB provides a quantitative and graphical means of describing the envelope of acceptable performance for specific dynamic situations. Experimental results of driver responses may then be compared to CPB. From the simulator experiment cited above, the ratio of the number of driver

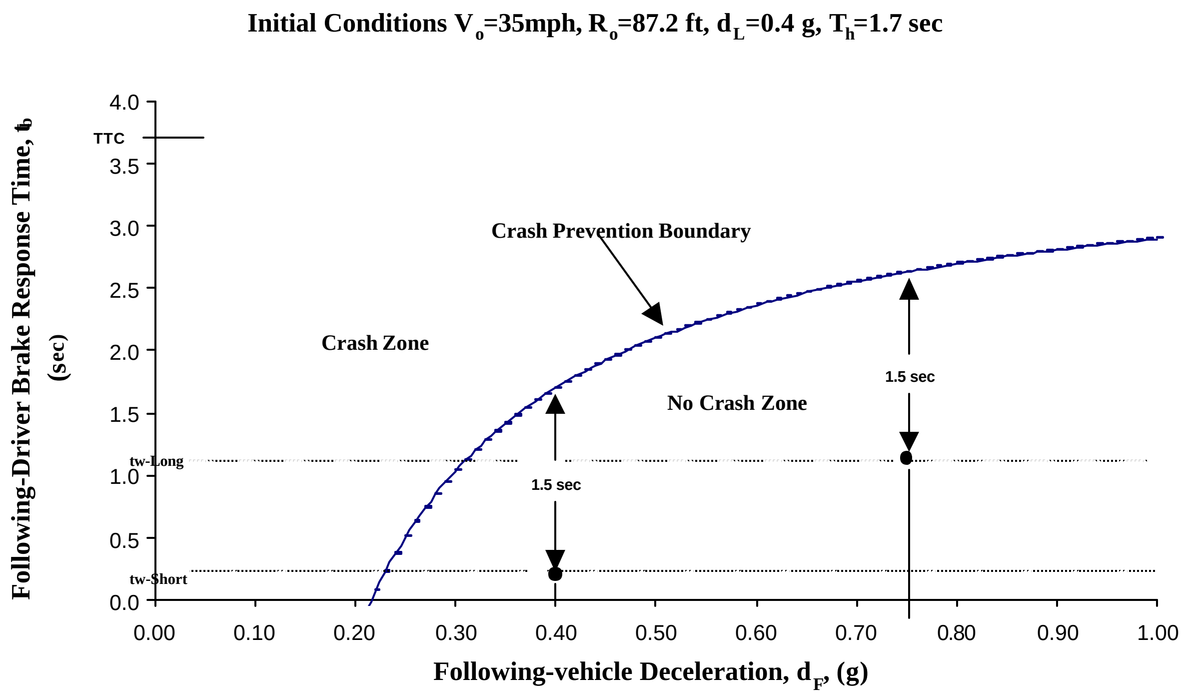

Figure 2. Sample Crash Prevention Boundary

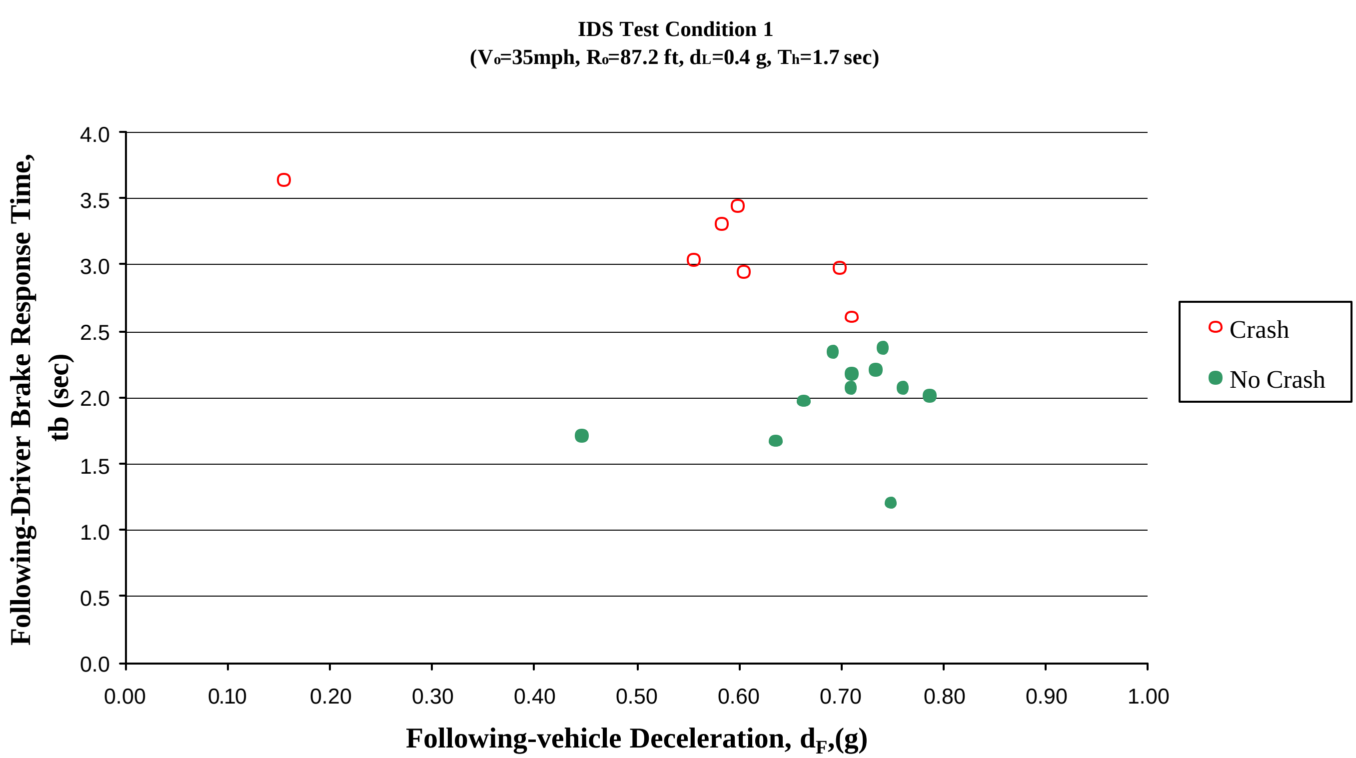

Figure 3. Driver Performance Experimental Results from Simulator Test Condition 1

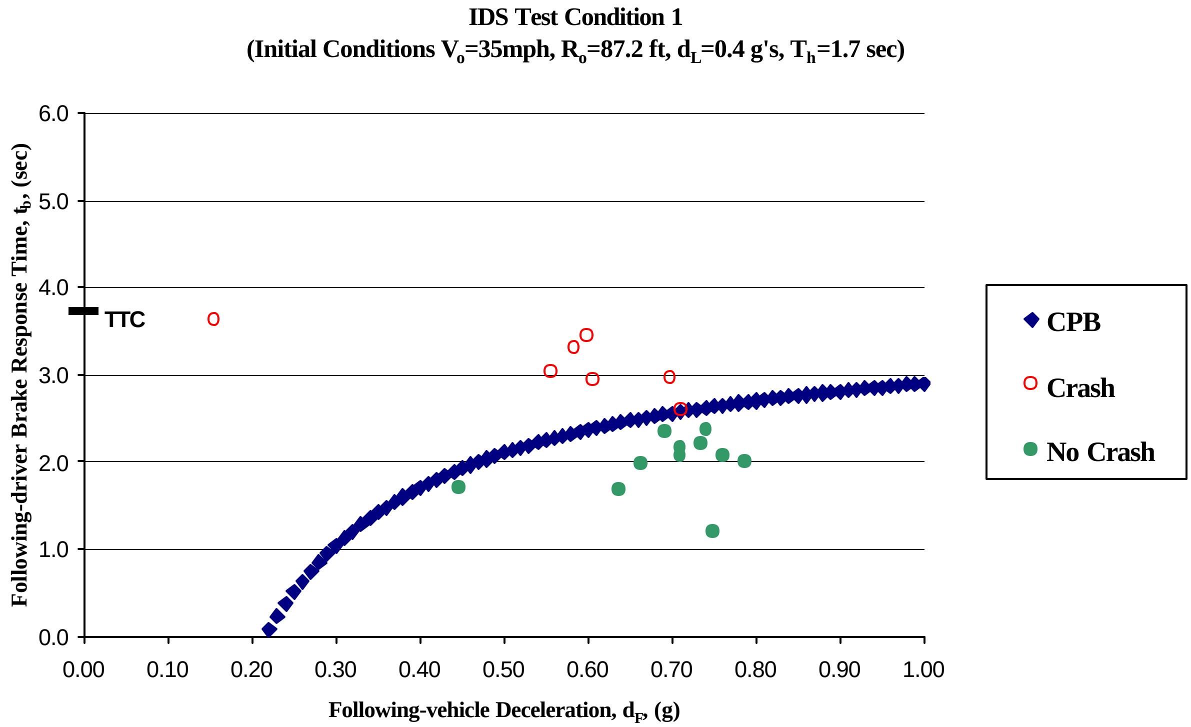

Figure 4. Simulator Driving Results With CPB

responses above the CPB to the total number of driver responses for conditions with and without warnings can be obtained. These ratios are estimates of the crash probability for each set of conditions. Given the probability of a crash, the effectiveness, E, of a warning system may be computed as follows[12]:

$$E = (P_{c,w/o} - P_{c,w})/P_{c,w/o}$$

where $P_{c,w/o}$ is the probability of a crash without a warning and $P_{c,w}$ is the probability of a crash with a warning. The values of E for the four sets of initial conditions are given in Table 2. The values of crash probability are given in column 4. Drivers who steered instead of braking to avoid a crash are not included in these results.

When effectiveness is compared for short vs. long warning, it can be seen that the short warning is more effective than the long warning in eliminating crashes in all situations.

Effectiveness also is seen graphically by a comparison of the number of points on each side of the CPB thus gaining perspective on the significance of the estimates. One of these perspectives is the level of crash severity. A number of observers have noted that calculations of effectiveness such as those above do not include consideration of the relative importance of more severe crashes. Although, not included quantitatively in this paper, it can be shown that relative speed at the time of impact is related to the distance a point is from the CPB. Hence a combination of graphically based insights and appropriate calculation procedures can provide additional estimates of the impact of a warning on overall crash-caused harm.

Warning Type	Test Condition	Total Tests	Crash Probability	Warning Effectiveness
Short (0.40g) ($P_{c,w}$)	2	19	0/19	1.00
	5	19	2/19	0.80
	8	19	1/19	0.88
	11	19	4/19	0.70
	Total	76	7/76	0.82
Long (0.75g) ($P_{c,w}$)	3	18	3/18	0.54
	6	19	5/19	0.52
	9	17	5/17	0.33
	12	16	5/16	0.55
	Total	70	18/70	0.50
No Warning ($P_{c,w/o}$)	1	18	7/18	
	4	18	10/18	
	7	16	7/16	
	10	17	12/17	
	Total	69	36/69	

Table 2. IDS Test Results

A third observation relates to the relative ease of identifying interesting features of experimental data. Two features of the driving simulator results are discussed here.

The first feature is the difference in baseline performance between the cases that started with long separation (i.e. test condition 10 which has an initial range of 201 feet) and the cases that started with shorter separation (between 88 and 137 feet for the other three test conditions). From the Figures B-7 and B-8 in Appendix B it can be seen that the cluster of points for test condition 10 (longer initial separation) is located somewhat above the CPB while the cluster of points for test conditions 1, 4 and 7 are almost evenly divided on both sides of the CPB. This difference in location is also seen in crash probability for these (no warning) test conditions; test condition 10 has a crash probability of 0.7 while the probability of a crash for the other three is between 0.35 and 0.55.

Thus it appears that there may be something fundamentally different about driver performance in baseline test condition 10 than in the other three baseline conditions. One possibility is that at the longer initial range, the drivers were not able to perceive that the lead vehicle was decelerating at a level that would produce an imminent crash. This lack of perception could be the result of limited graphical fidelity in the driving simulator or it could be a limitation in ability to perceive relative motion. The data from the experiment is not adequate to reach definite conclusions on this question. However, a quick review of capability of perceiving a looming object can provide some insight.

Figure B-9 in Appendix B shows the relationship between the rate of change of the subtended angle of the lead-vehicle as seen by the driver of the following-vehicle and the distance between the vehicles. This is consistent with previous research with regard to the perception of a "looming" object [7, p 157]. The reference paper suggested that a rate of change of 0.003 radians per second is a threshold below which subjects are not able to perceive a significant relative motion. Figure B-9 shows that this threshold is reached at a longer range and after a larger change in range for test condition 10 than the other three conditions. Thus, the graphical nature of the CPB presentation for analyzing experimental data suggests a difference in the driver's perceived level of threat; and points the way to an approach for investigating the issue.

A second significant driving simulator feature is the distribution of actual performance relative to the assumed performance that is the basis of the warning. For the three conditions with relatively short range at the beginning of the event, a summary of performance of the drivers is as follows.

For the short warning (assumed following-vehicle level of deceleration of 0.4g), the average reaction time (the time between a warning being given and application of the brakes) was 1.8 seconds, close to the assumed value of 1.5 seconds. For the long warnings (assumed level of deceleration of 0.75g) the average reaction time was 2.3 seconds, greater than the assumed value of 1.5 seconds. Similarly, the average deceleration for the short warning of 0.59g was greater than the assumed level of 0.4g; but for the long warning the average deceleration of 0.62g was closer to the assumed level of 0.75g. While these differences suggest that the drivers braked at the same level, it is not clear why on average their responses took longer for long warnings.

FUTURE WORK

Some future applications and extensions of CPBs include further analysis of rear-end crash conditions. This will include an analysis of naturalistic driving data from an intelligent cruise control field operational test, and data from other naturalistic driving experiments. It will also include derivation of CPB expressions for other families of rear-end crashes and for other types of crashes such as road departure.
A third extension would lead to better understanding of the concept of nuisance warnings and near-crash conditions and is useful as a measure of "seriousness" of situations, i.e. it may be used as parameter in distribution of responses.

CONCLUSIONS

This paper has introduced the idea of an analytically derived deterministic crash prevention boundary and has shown its application to the analysis of rear-end crash data. The analysis of data from an experiment in a driving simulator led to additional insights into driver performance in situations where a rear-end crash was imminent. One insight is the possibility that limitations on driver's ability to perceive relative motion may have significant impact on crash prevention performance. Another insight is that extensions of the framework presented here may provide a better understanding of the relative severity of crashes. These insights may lead to additional testing or analysis to refine further the understanding of driver performance.

ACKNOWLEDGEMENTS

Many thanks to the NHTSA staff, especially Peter Martin of the Advanced Safety Systems Research Division as well as Wassim Najm of the Volpe National Transportation Systems Center for reviews, valuable comments, and contributions to this paper.

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APPENDIX A – Derivation of Expressions for Crash Prevention Boundary

A.1 DERIVATION OF CROSSOVER DECELERATION, d_F^*

Consider the case as seen in Figure 1 where the slowing vehicles just touch, bumper-to-bumper, without crashing. For this situation to occur, the following-vehicle deceleration, d_F, must be of a certain level that is dependent on the time of brake application. A subset of this case occurs when both vehicles stop at precisely the same moment. This will happen only at a single deceleration level, d_F^*. If d_F is greater than d_F^*, the lead vehicle will pull away after they touch. If d_F is less than d_F^*, the lead-vehicle will stop before the following-vehicle (but they will eventually end up bumper-to-bumper). The term, d_F^*, is defined as the crossover deceleration and is the basis of the Crash Prevention Boundary.

An expression for d_F^* may be derived by considering the no-crash case when the vehicles stop simultaneously and are bumper-to-bumper. Suppose the initial conditions of range, R_o, velocity, V_o, and lead-vehicle deceleration, d_L, are given and t_b is the time of following-vehicle driver braking in reaction to a warning. The sequence of events is then: $t = 0$, t_b, and t_s.

Let $X_F(t_s)$ and $X_L(t_s)$ be the vehicle positions at time t_s. At time, t_s, the vehicles come to rest at and are just touching at which point both velocities are zero:

$$d(X_F(t_s))/dt = d(X_L(t_s))/dt = 0 \qquad \text{(A-1)}$$

and by definition,

$$d(X_L(t_s))/dt = V_0 - d_L t_s \qquad \text{(A-2)}$$

$$d(X_F(t_s))/dt = V_0 - d_F(t_s - t_b) \qquad \text{(A-3)}$$

in addition

$$t_s = V_0/d_L, \text{ and} \qquad \text{(A-4)}$$

$$t_s - t_b = V_0/d_F. \qquad \text{(A-5)}$$

The positions X_F and X_L of the vehicles then at time t_s are:

$$X_F(t_s) = t_b V_0 + V_0(t_s - t_b) - d_F(t_s - t_b)^2/2 \qquad \text{(A-6)}$$

$$X_L(t_s) = R_0 + t_s V_0 - d_L t_s^2/2 \qquad \text{(A-7)}$$

Equating A-6 and A-7 gives

$$V_0^2/d_L - V_0^2/2d_F = R_0 + V_0^2/2d_L \qquad \text{(A-8)}$$

$$V_0^2[1/d_L - 1/2d_F]/2 = R_0 + V_0^2/2d_L \qquad \text{(A-9)}$$

Solving for d_F we have the desired expression for d_F^*:

$$\boxed{d_F = d_L V_0^2/(V_0^2 - 2d_L R_0) = d_F^*} \qquad \text{(A-10)}$$

Thus, given a set of initial conditions of d_L, V_0, and R_0 when $d_F < d_F^*$, the lead-vehicle stops before or at the same time as the following-vehicle. If the same initial conditions hold and $d_F > d_F^*$ the following-vehicle stops before the lead-vehicle. For this second condition ($d_F > d_F^*$) the bumper-to-bumper condition occurs while both vehicles are still moving.

A.2 BRAKE APPLICATION TIME IF THE LEAD-VEHICLE STOPS BEFORE THE FOLLOWING-VEHICLE.

In this scenario, the following-vehicle deceleration is less than d_F^*(see Appendix A.1). At the end of the motion, the vehicles are stationary and bumper-to-bumper:

$$X_F(t_s) = X_L(t_s) \qquad \text{(A-11)}$$

And their final positions are

$$X_F(t_s) = V_0 t_b + V_0^2/(2d_F) \qquad \text{(A-12)}$$

$$X_L(t_s) = R_0 + V_0^2/(2d_L) \qquad \text{(A-13)}$$

Substituting into the first equation we have,

$$V_0 t_b + V_0^2/(2d_F) = R_0 + V_0^2/(2d_L) \qquad \text{(A-14)}$$

Solving for t_b gives the relationship

$$\boxed{t_b = R_0/V_0 + V_0[1/d_L - 1/d_F]/2} \qquad \text{if } d_F < d_F^* \qquad \text{(A-15)}$$

A.3 BRAKE APPLICATION TIME IF THE FOLLOWING-VEHICLE STOPS BEFORE THE LEAD-VEHICLE.

In this case the following-vehicle deceleration is greater than d_F^*. The closest approach occurs while the two vehicles are still in motion so that they just touch at which time their velocities are equal. Thus, at the point of <u>closest approach</u> of the two vehicles , t_c, requires the relationships that the positions and speeds be equal as follows:

$$X_F(t_c) = X_L(t_c) \qquad \text{(A-16)}$$

$$dX_L(t_c)/dt = dX_F(t_c)/dt \qquad \text{(A-17)}$$

Also note that at closest approach the range rate, dR/dt, changes sign going from negative to positive, i.e.

$$dR/dt < 0 \qquad 0 < t < t_c \qquad \text{(A-18)}$$

$$dR/dt > 0 \qquad t > t_c \qquad \text{(A-19)}$$

The positions of the two vehicles at the time of closest approach, t_c, are:

$$X_L(t_c) = R_0 + V_0 t_c - (d_L/2)t_c^2 \qquad \text{(A-20)}$$

$$X_F(t_c) = V_0 t_c - (d_F/2)(t_c - t_b)^2 \qquad \text{(A-21)}$$

Substituting into the position equation, A-16, above,

$$V_0t_c - (d_F/2)(t_c - t_b)^2 = R_0 + V_0t_c - (d_L/2)t_c^2 \quad \text{(A-22)}$$

Furthermore, the speed equation, A17, for the two vehicles at t_c may be written as,

$$dX_L(t_c)/dt = V_0 - d_Lt_c \quad \text{(A-23)}$$

$$dX_F(t_c)/dt = V_0 - d_F(t_c - t_b) \quad \text{(A-24)}$$

which may be equated at the critical time, t_c:

$$V_0 - d_Lt_c = V_0 - d_F(t_c - t_b) \quad \text{(A-25)}$$

Rearranging equation A-25 gives,

$$t_bd_F = t_c(d_F - d_L) \quad \text{(A-26)}$$

and solving for t_b yields:

$$t_b = [(d_F - d_L)/(d_F)]t_c \quad \text{(A-27)}$$

Substituting this into equation A-22 above and simplifying to obtain an expression for t_c gives,

$$- (d_F/2)[t_c - ((d_F - d_L)/(d_F))t_c]^2 = R_0 - (d_L/2)t_c^2 \quad \text{(A-28)}$$

$$-(d_F/2)[d_Lt_c/d_F]^2 = R_0 - (d_L/2)t_c^2 \quad \text{(A-29)}$$

$$[d_L/2 - (d_F/2)(d_L/d_F)^2]t_c^2 = R_0 \quad \text{(A-30)}$$

$$(d_L/2)[1 - d_L/d_F]t_c^2 = R_0 \quad \text{(A-31)}$$

$$\text{then } t_c = [2R_0/\{d_L(1 - d_L/d_F)\}]^{1/2} \quad \text{(A-32)}$$

Substituting into equation A-27 for t_b results in:

$$t_b = [(d_F - d_L)/d_F][2R_0/\{d_L(1 - d_L/d_F)\}]^{1/2} \quad \text{(A-33)}$$

rearranging terms and simplifying gives the following expression:

$$\boxed{t_b = [(2V_0T_h/d_L)(1 - d_L/d_F)]^{1/2}} \quad \text{if } d_F > d_F^* \quad \text{(A-34)}$$

In summary then for both conditions:

$$t_b = R_0/V_0 + (V_0/2)[1/d_L - 1/d_F] \quad \text{if } d_F < d_F^* \quad \text{(A-15)}$$

$$t_b = [(2V_0T_h/d_L)(1 - d_L/d_F)]^{1/2} \quad \text{if } d_F > d_F^* \quad \text{(A-34)}$$

A.4 TIME TO COLLISION EXPRESSIONS

As developed in Sections A.1 to A.3, given the condition of lead-vehicle braking, it is necessary to establish the governing mathematical relationships between d_F and t_b in relationship to the result of the conflict. For a specific rear-end driving scenario starting with initial velocity, V_0, initial range, R_0, and lead-vehicle deceleration level, d_L, there is a following-vehicle deceleration level, d_F, that determines a brake application time as described by the equations A-15 and A-34 which are the CPB equations.

It is often convenient to relate this expression to the time to collision, (TTC). TTC is the value in seconds at which collision will occur if the following-vehicle driver does not brake at all. TTC is obviously a function of lead-vehicle deceleration, d_L.

If d_L is relatively large, a collision will occur after the lead-vehicle has come to a stop. If d_L Is relatively small, the collision will occur before the lead-vehicle has come to a stop. Thus, for every initial value of R_0 and V_0 there is a value of d_L that separates these two collision conditions. That value of d_L, denoted by d_L*, corresponds to the value for which the collision occurs at the instant that the lead-vehicle comes to a stop. The logic for development of the relationship for the time-to-collision (TTC) is similar to that in section A.1. However, the difference in the case discussed here from that of A.1 is that the following-vehicle takes no evasive braking action. To determine d_L*, the lead-vehicle will take V_0/d_L seconds to come to a stop. During this time, the lead-vehicle will travel a distance of $V_0^2/2d_L$ and the following-vehicle will travel V_0^2/d_L. The locations for each vehicle after V_0/d_L seconds are $R_0 + V_0^2/2d_L$ and V_0^2/d_L, respectively for the lead and the following-vehicles. Since these locations must be the same, equating these expressions provides the relationship for d_L*:

$$R_0 + V_0^2/2d_L = V_0^2/d_L \quad \text{(A-35)}$$

And solving for d_L yields d_L*:

$$d_L^* = V_0/(2T_h) \quad \text{(A-36)}$$

In order to find expressions for TTC1 and TTC2, it will be sufficient to use equations already derived.

For the first condition using equation A-14 with the assumption that there is no braking by the following-vehicle and that t_b is defined as TTC1, gives:

$$V_0(\text{TTC1}) = R_0 + V_0^2/(2d_L) \quad \text{(A-37)}$$

Solving for TTC1 and expressing the result in terms of T_h gives the espression

$$\text{TTC1} = T_h + V_0/2d_L \quad \text{if } d_L > d_L^* \quad \text{(A-38)}$$

Then, for the second condition from equation A-31 where there is no braking by the following-vehicle and t_c is defined as TTC2, gives

$$\text{TTC2} = (2V_0T_h/d_L)^{1/2} \quad \text{if } d_L < d_L^* \quad \text{(A-39)}$$

Then in order to express the original equations in terms of TTC values, we have

$$t_b = \text{TTC1} - V_o/(2d_F), \quad \text{if } d_F < d_F^* \quad \text{(A-40)}$$

$$t_b = TTC2(1 - d_L/d_F)^{1/2} \quad \text{if } d_F > d_F^* \qquad \text{(A-41)}$$

Thus, it is seen that d_F* and d_L* are analogous conditions that must hold simultaneously in relation to d_F and d_L for the proper expression of t_b in terms of TTC. Therefore, a hypothetical boundary of t_b vs. d_F can be formed for a set of initial conditions of R_0, d_L, and T_h which shall be termed the crash prevention boundary (CPB). The CPB may either be expressed in terms of equations A-15 and A-34 or by equations A-40 and A-41 with their attendant conditions.

APPENDIX B

SIMULATOR RESULTS

Tables 1 and 2, and the accompanying text, summarize a series of experiments that were run on the Iowa Driving Simulator. Figures B-1 through B-8 present details of the crash prevention performance for each subject in the experiment. Each figure contains performance data for a specific set of initial conditions in both the baseline condition, i.e. no warning was provided, and where a warning was provided. Each figure also includes the design point for the warning. The design point, or reference performance, for the "short" warning was a reaction time to the warning of 1.5 seconds and a braking level which produced a constant 0.4g deceleration. The design point for the "long" warning was a reaction time of 1.5 seconds and a constant deceleration of 0.75g. The crash prevention boundary that corresponds to the initial condition as well as the time-to-collision at the beginning of the event are also shown in each figure.

Figure B-1. IDS Test Conditions 1 and 2
(V=35mph, R=87.2 ft, dL=0.4 g's, Th=1.7 sec)

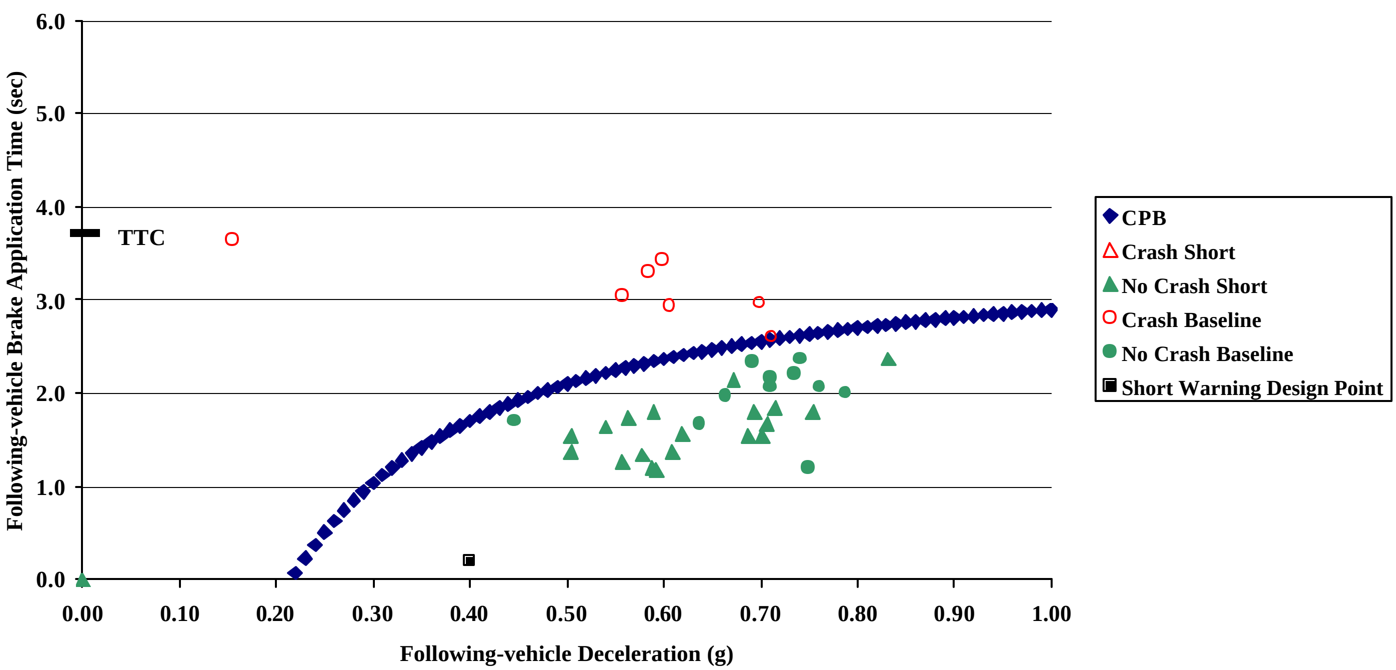


Figure B-2. IDS Test Conditions 1 and 3
(V=35mph, R=87.2 ft, dL=0.4 g's, Th=1.7 sec)

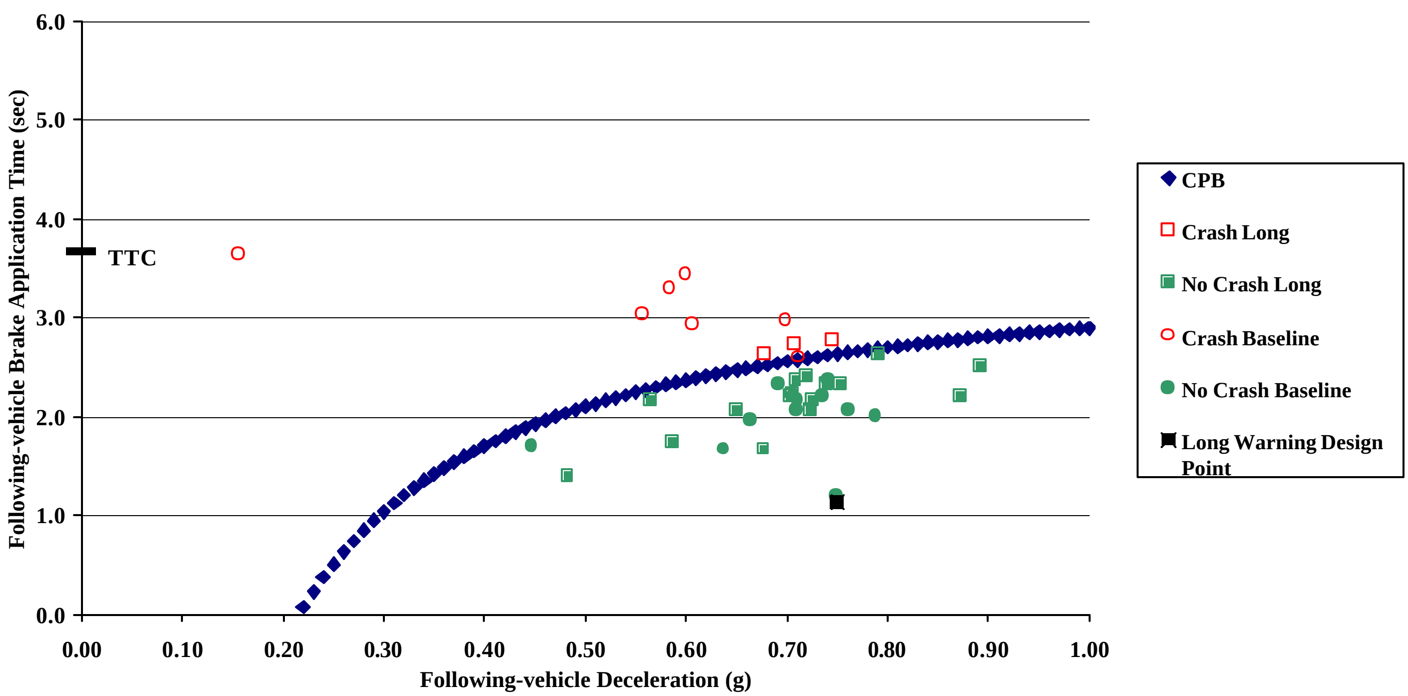


Figure B-3. IDS Test Conditions 4 and 5
(V=35mph, R=128.3 ft, dL=0.55 g's, Th=2.5 sec)

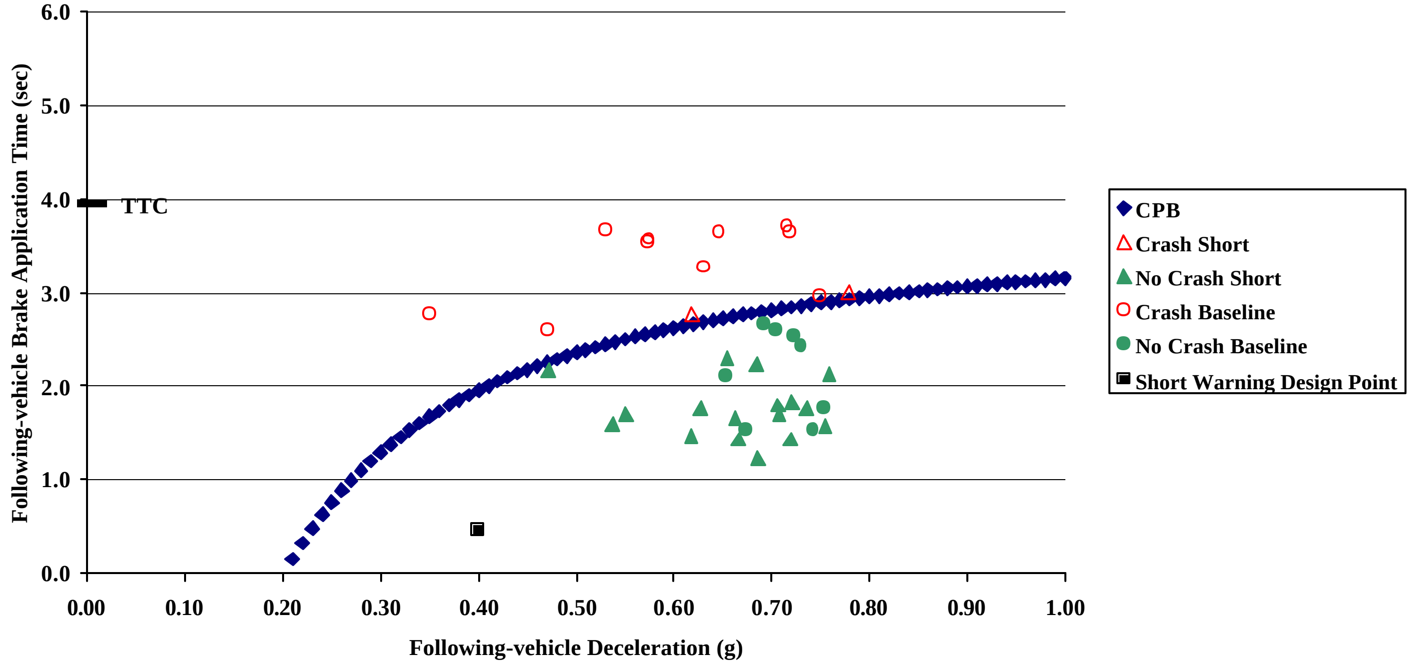


Figure B-4. IDS Test Conditions 4 and 6
(V=35mph, R=128.3 ft, dL=0.55 g's, Th=2.5 sec)

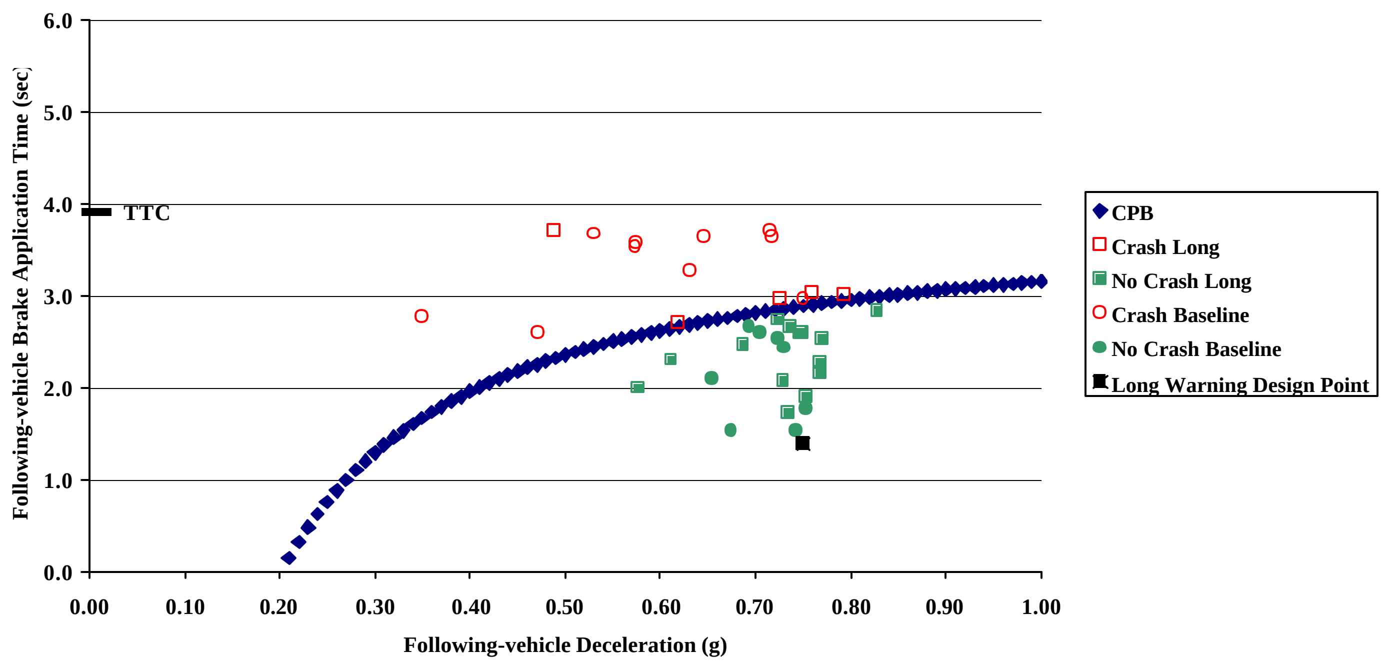


Figure B-5. IDS Test Conditions 7 and 8
(V=55 mph, R=137.1 ft, dL=0.4 g's, Th=1.7 sec)

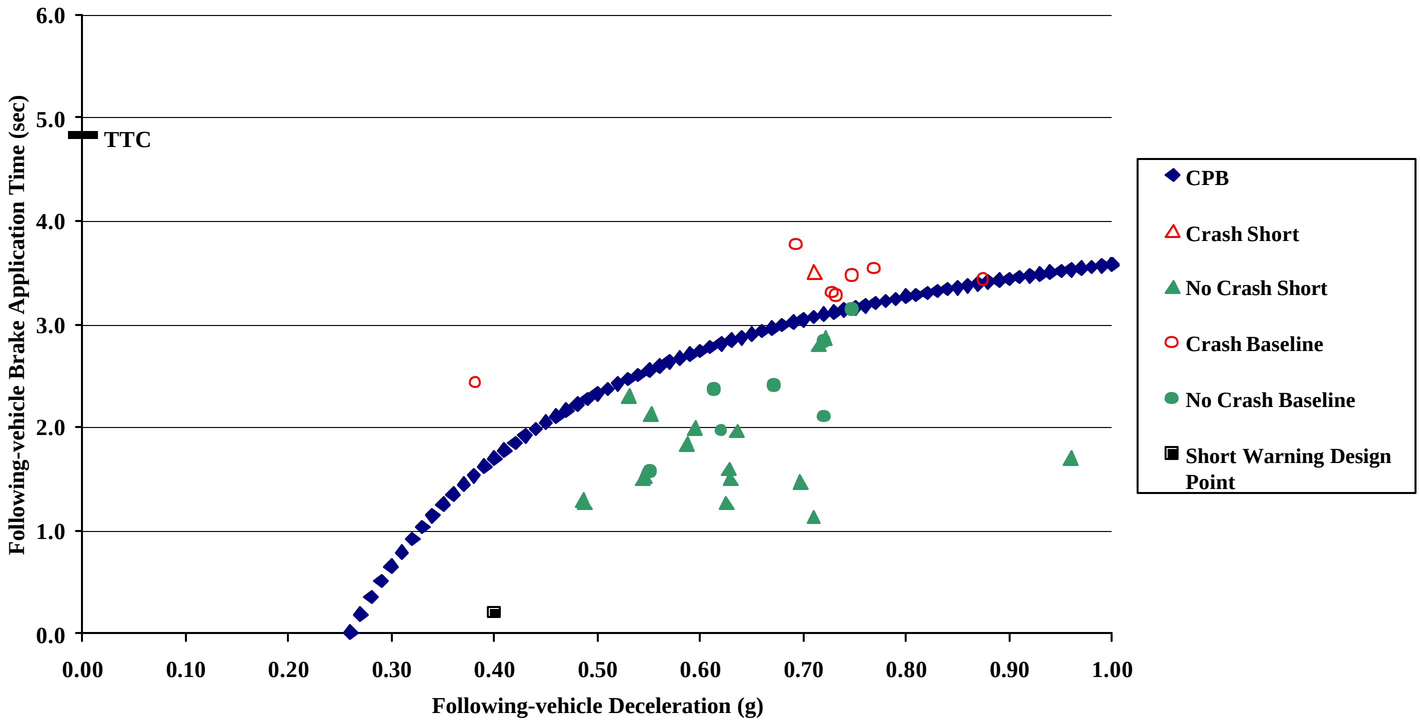


Figure B-6. IDS Test Conditions 7 and 9
(V=55 mph, R=137.1 ft, dL=0.4 g's, Th=1.7 sec)

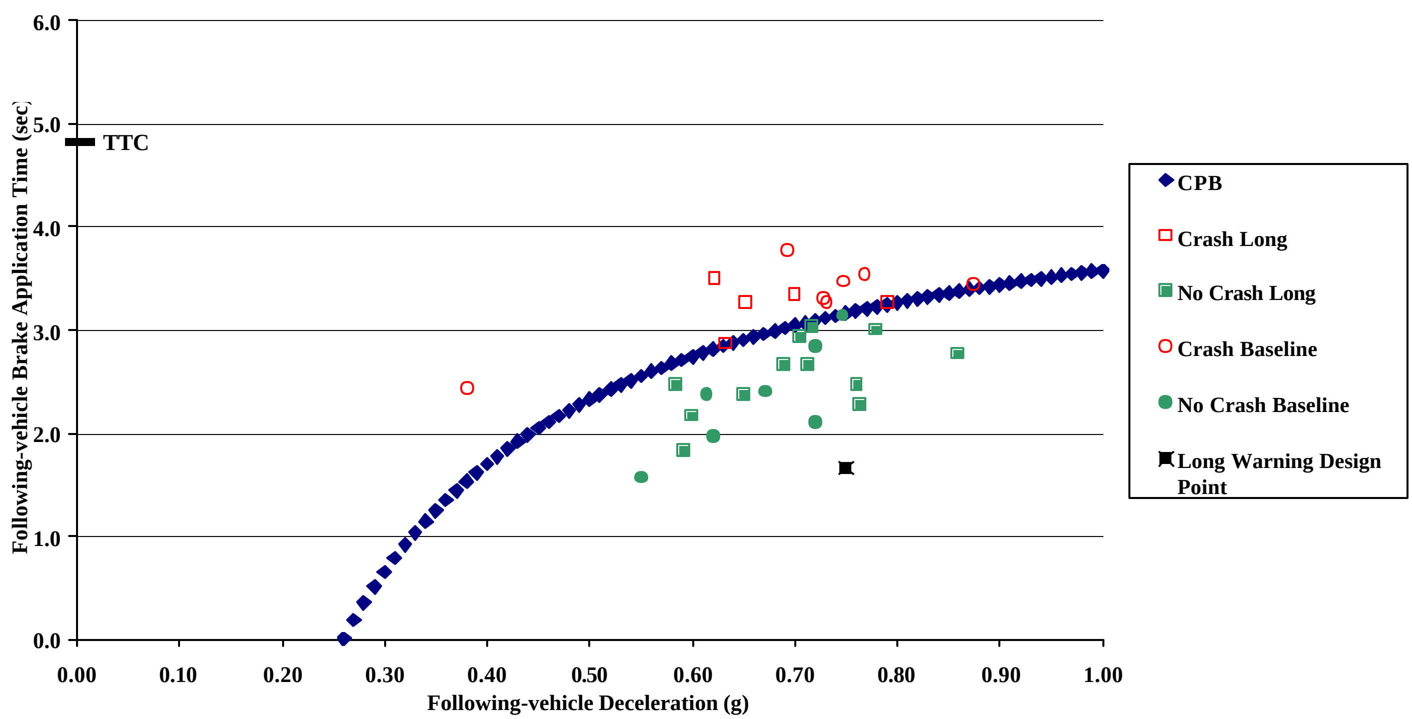


Figure B-7. IDS Test Conditons 10 and 11
(V=55 mph, R=201.7 ft, dL=0.55 g's, Th=2.5 sec)

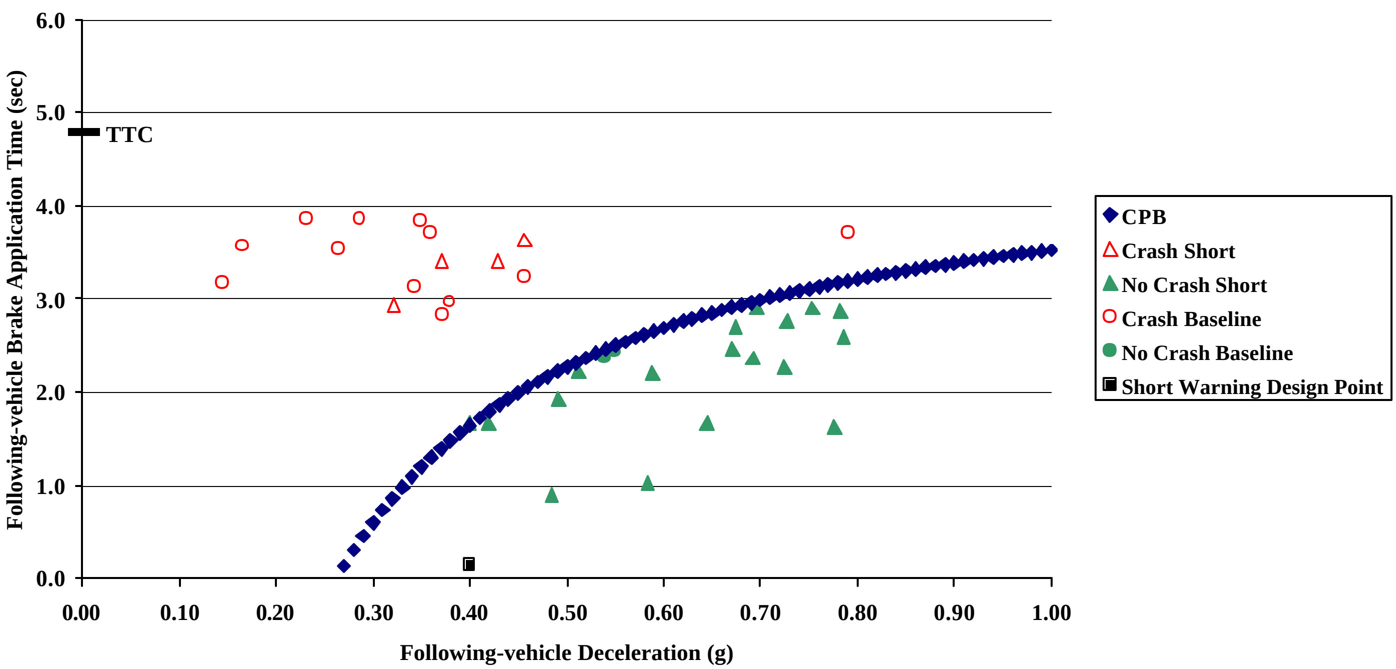


Figure B-8. IDS Test Conditons 10 and 12
(V=55 mph, R=201.7 ft, dL=0.55 g's, Th=2.5 sec)

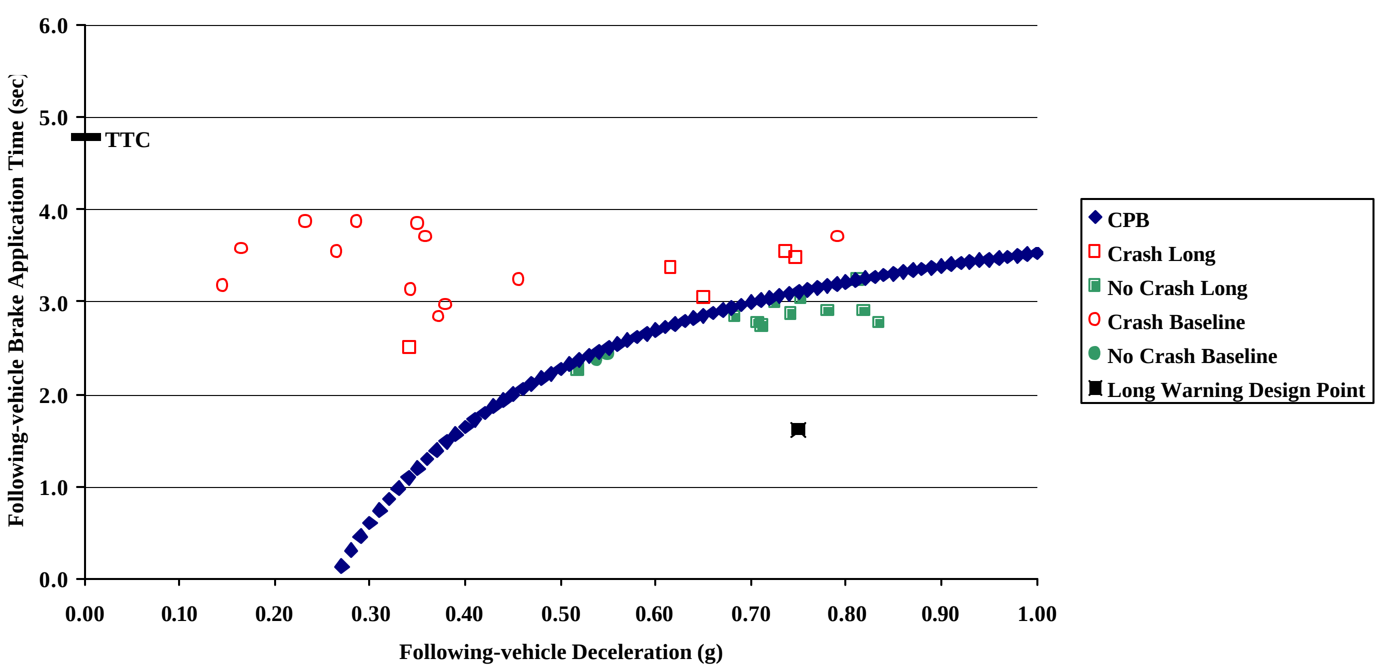
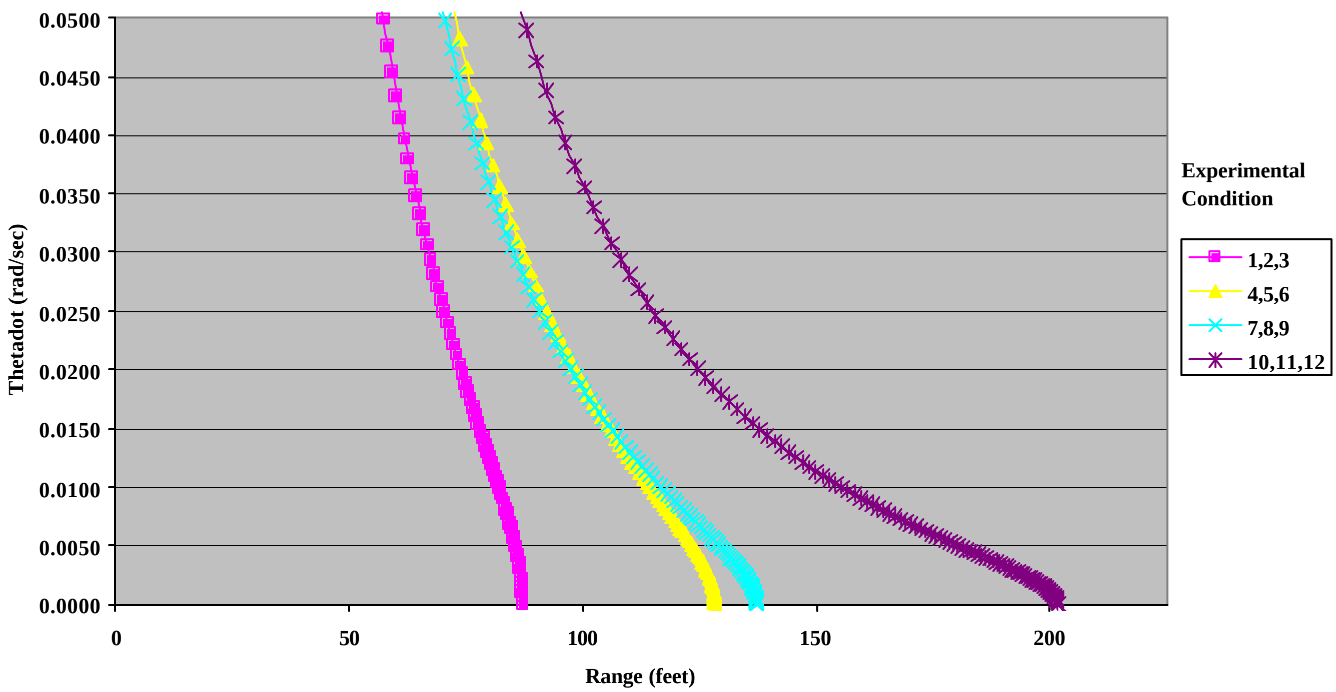


Figure B-9. Looming Effect for IDS Experiments



APPENDIX C. LIST OF FIGURES AND TABLES

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APPENDIX D. TERMS AND DEFINITIONS

ACC, Adaptive Cruise Control
CAMP, Crash Avoidance Metrics Partnership
CPB, Crash Prevention Boundary
d_F, average following-vehicle deceleration
d_L, average lead-vehicle deceleration
E, Effectiveness
FOCAS, Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems
IC, Initial Conditions
ICC, Intelligent Cruise Control
IDS, Iowa Driving Simulator
JHU/APL, Johns Hopkins University Applied Physics Laboratory
NHTSA, National Highway Transportation Safety Agency
Range, Separation distance between two vehicles
R_0, Range at time of Initial Conditions
t_c, time of closest approach of two vehicles
T_h, headway at time of initial conditions
t_b, brake response time of following-vehicle
t_w, warning time
TTC, Time to Collision for following-vehicle
V_0, Velocity at time of Initial Conditions

Errata:

Please replace Figures B-7 and B-8 with the following figures.