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NHTSA Rear-End Collision Alert Algorithm

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16. Abstract

As part of its ongoing research activities supporting the development, testing and evaluation of collision warning systems, the National Highway Traffic Safety Administration (NHTSA) developed an experimentally-based rear-end collision warning algorithm and sponsored analysis of the algorithm using test data collected during an intelligent cruise control field operational test.

In October of 1999, NHTSA sponsored a joint research effort with the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to refine the algorithm previously developed by NHTSA and translate it into structured C code capable of running in the real-time processor environment of a prototype vehicle-based system.

This report describes the theory of operation of the NHTSA Algorithm and its theoretical performance under a defined set of typical rear-end collision scenarios. Test data from a series of controlled test track studies are discussed and an estimate of the number of rear-end collisions that could be avoided using the NHTSA Algorithm is also presented in the report.
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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed an algorithm for use with rear-end collision warning systems for the National Highway Traffic Safety Administration (NHTSA). The algorithm processes data received from a vehicle-mounted radar and other vehicle subsystems to generate alerts to help drivers avoid rear-end collisions. This work was performed under the NHTSA Alert Algorithm Development Program from October 1999 through June 2002. This report describes the theory of operation of the algorithm, its theoretical performance under a set of defined operational scenarios, its performance for a series of verification tests, and its performance as evaluated by a simulation conducted to determine a system probability of collision.

KEYWORDS: Alert Algorithm
                 Intelligent Transportation Systems (ITS)
                 Rear-End Collision Warning System

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EXECUTIVE SUMMARY

ES.1   <u>INTRODUCTION</u>

The Johns Hopkins University Applied Physics Laboratory has developed for the National Highway Traffic Safety Administration (NHTSA) an alert algorithm for use with rear-end collision warning systems. The algorithm, which is an extension of previous NHTSA-sponsored work in rear-end collision avoidance, alerts drivers to potentially dangerous driving situations and the need to take evasive action. It has been integrated along with a General Motors (GM)-developed algorithm into a prototype collision warning system developed by GM for use during the Automotive Collision Avoidance System (ACAS) Field Operational Test (FOT). This document describes the alert algorithm and analyzes its performance.

ES.2   <u>ALGORITHM DESCRIPTION</u>

The objective of the NHTSA Algorithm is to issue collision alerts that allow the driver of the host vehicle to stop or approach no closer than a designated distance behind a stopped or decelerating lead vehicle. Its features are summarized in Table ES-1. The following assumptions and design decisions were implicit in the development of the algorithm:

  a. The lead vehicle will maintain its current level of deceleration.

  b. The host vehicle will maintain its current acceleration for a fixed reaction time and then decelerate at a constant, prescribed level.

  c. Alerts are inhibited for oncoming (including backing) vehicles.

  d. Alerts are inhibited when the host vehicle velocity is below 25 mph.

  e. Situations where the host vehicle is closely following the lead vehicle are handled by a special tailgating mode of operation.

  f. Situations where the vehicle's Adaptive Cruise Control (ACC) system is on and actively tracking a lead vehicle are handled by a special ACC mode of operation.

Table ES-1 NHTSA Algorithm Features

Operating Modes:	
Standard	Used for normal driving situations Based on a calculated miss distance
Tailgating	Used when closely following the lead vehicle Based on range and lead vehicle braking
ACC	Used in conjunction with ACC subsystem of ACAS FOT Collision Warning System
Input Parameters	
Host Vehicle Velocity	Supplied by host vehicle
Host Vehicle Acceleration	Supplied by host vehicle
Relative Acceleration	Supplied by collision warning system
Range	Supplied by collision warning system
Range Rate	Supplied by collision warning system
System Parameters	
Time Interval	Input parameters updated and calculations made every 100 ms
Reaction Time	Driver and system delay of 1.5 s (0.5 s when brake applied)
Assumed Maximum Braking Level	Imminent alert miss-distance calculations use 0.55 g, varies by warning sensitivity level for cautionary alerts
Warning Sensitivity Level	Three levels - Near, Mid, Far (aggressive to conservative drivers) used to modify braking level for cautionary alerts
Brake Applied	Supplied by host vehicle
ACC State	Supplied by ACC subsystem of collision warning system
Miss-Distance Threshold	A fixed 2-m component plus a time-interval look ahead component
Alert Levels	No alert, two levels of cautionary alerts (early and intermediate), and imminent crash alert
Alert Suppression	Oncoming vehicles, host vehicle velocity below threshold

        The primary input parameters required by the NHTSA Algorithm are host vehicle velocity, host vehicle acceleration, relative acceleration, range, and range rate. The decision to issue an alert is made every 100 ms upon parameter update by the collision warning system. The standard mode of the algorithm computes the projected miss distance at each time interval based on a constant host vehicle deceleration, a reaction time, and measured estimates of the input parameters. This projected miss distance is then compared with a miss-distance threshold to determine if a warning should be issued.

        The NHTSA Algorithm provides three alert levels: early, intermediate, and imminent. The imminent alert level indicates that there is danger of a collision based on the driver responding with the maximum braking level of -0.55 g after a set reaction time. The driver reaction time, which includes the driver and system delays between warning and vehicle response, is

normally set to 1.5 s. If the driver is pressing the brake, it is reduced to 0.5 s. Early and intermediate cautionary alert levels provide warning of collisions based on the host vehicle braking at reduced levels. These are selected based on the driver's choice of a sensitivity setting (Near, Mid, or Far). It is expected that a more aggressive driver would choose the Near sensitivity level, which implies a desire for shorter headways between the host and lead vehicles, and that the most conservative drivers would choose the Far sensitivity level, which implies a desire for longer headways.

The standard mode of the algorithm provides sufficient warning when the host vehicle is approaching a slow or stopped lead vehicle or when sufficient headway is present to adequately estimate the deceleration of a lead vehicle that is braking. Two additional modes, tailgating and ACC, operate with the standard mode to handle special conditions. Tailgating mode provides cautionary alerts based on range to advise the driver that deceleration by the lead vehicle could require a quick braking response. An imminent collision alert is provided in a tailgating situation when a lead vehicle deceleration of −0.2 g is detected. The NHTSA Algorithm was developed to work in conjunction with the ACC subsystem of the ACAS FOT collision warning system. When the vehicle's ACC system is turned on, the NHTSA Algorithm defers to the alert function built into the ACC system. The ACC system, however, does not recognize stationary targets; thus, the NHTSA Algorithm continues to search for stopped vehicle warning situations when the ACC system is on.

ES.3   ALGORITHM PERFORMANCE

The NHTSA Algorithm was subjected to analyses, tests, and simulation to determine its performance. The analyses and tests included theoretical analyses and verification tests with the alert algorithm installed in a test vehicle equipped with a prototype collision warning system. Two sets of theoretical analyses were performed. The first examined the performance of the alert algorithm under the assumption of perfect input data. This was done for three operational scenarios representing the pre-crash conditions for many of the rear-end collisions that the collision warning system is meant to prevent. The second analysis examined the effects of measurement noise and driver variability on the performance of the alert algorithm.

The first analysis determined the performance of the algorithm with perfect input data. Examples of the algorithm's imminent alert ranges are presented in Table ES-2. The second analysis indicated that the performance of the algorithm, in terms of Probability of False Alarm (PFA) versus Probability of a Miss (P_{miss}), is set by the choice of estimated driver reaction time and assumed host vehicle deceleration. The NHTSA Algorithm with $A_{Hmax,est} = -0.55$ g and $T_{R,est} = 1.5$ s operates at a PFA of 0.65 and a P_{miss} of 0.03 for a stopped lead vehicle scenario. Furthermore, this analysis indicated that the error in estimating the driver response (braking level and reaction time) has a greater impact on algorithm performance than the error in measuring the vehicle dynamics, with the measurement noise having little effect on overall performance.

Table ES-2 NHTSA Algorithm Theoretical Imminent Alert Ranges in Meters

Scenario	Host Vehicle Speed				
	30 mph	40 mph	50 mph	60 mph	70 mph
Stopped Lead Vehicle	40 m	60 m	84 m	112 m	143 m
Slower Lead Vehicle [a]	24 m	25 m	25 m	25 m	26 m
Slower Lead Vehicle [b]	24 m	41 m	61 m	84 m	112 m
Braking Lead Vehicle [c]	30 m	31 m	31 m	31 m	32 m
Braking Lead Vehicle [d]	40 m [e]	56 m	63 m	66 m	67 m

[a]Lead vehicle 20 mph slower than host vehicle.

[b]Lead vehicle at constant speed of 10 mph.

[c]Same initial speed, -0.3 g braking, 35 m initial range.

[d]Same initial speed, -0.3 g braking, 85 m initial range.

[e]Lead vehicle comes to a stop prior to alert being issued.

Verification testing was conducted with the NHTSA Algorithm installed in a vehicle equipped with the prototype ACAS FOT collision warning system. A series of tests was used to verify the proper operation of the algorithm. In addition, unstructured testing was conducted on public roads. The theoretical performance of the standard mode of the algorithm was verified during this testing; cautionary and imminent collision alerts were issued at the appropriate times. Table ES-3 presents representative results from this testing. The tailgating mode of the algorithm provided cautionary alerts at the expected ranges and imminent alerts were issued within 0.7 s of lead vehicle braking (at approximately –0.3 g) at a range of approximately 16 m.

It was noted that in some scenarios the performance of the algorithm was dependent on the ability of the radar system to report valid targets on curves and at longer ranges. Algorithm performance was most affected when the host vehicle was traveling at higher speeds. An example of this was noted for the 60-mph stopped lead vehicle scenario for which a target was not reported to the alert algorithm until after the NHTSA Algorithm's theoretical imminent alert range was passed. In addition, data quality and resolution can also affect performance of the algorithm, resulting in alerts at other than the theoretical ranges. For example, the alert for the slower lead vehicle test in Table ES-3 was issued earlier than expected due to the resolution of A_R.

Finally, a detailed simulation of the performance of the NHTSA Algorithm was performed to estimate the proportion of rear-end collisions that could be avoided for an example scenario. The simulation showed that with the algorithm there was a probability of collision between 0.017 - 0.129 for the scenario of a 60-mph host vehicle approaching a stopped lead vehicle, depending on the reaction time model used.

Table ES-3 NHTSA Algorithm Test Performance

| Test | Imminent Warning Range (m) | | |
	Theoretical	Average Result	Comments
Stopped Lead Vehicle*	112	70	Alert issued immediately upon receipt of target from the radar system.
Slower Lead Vehicle**	61	69	Early alert due to resolution of relative acceleration.
Braking Lead Vehicle†	34	36	Braking profile did not exactly match specified test conditions.
*Host Vehicle Speed: 60 mph. **Host Vehicle Speed: 50 mph, Lead Vehicle Speed: 10 mph. †Host and Lead Vehicle Speeds: 60 mph, Lead Vehicle Braking: -0.3 g, Initial Range: 38 m.			

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Section 1

INTRODUCTION

1.1   <u>BACKGROUND</u>

A rear-end collision is defined as an on-road, two-vehicle collision in which the front of the vehicle in question impacts the rear end of another vehicle in its forward path. Both vehicles are moving forward in the same direction prior to the collision, although the vehicle in the forward path may have come to a stop. According to data from the General Estimates System (GES) and Fatality Analysis Reporting System databases, rear-end collisions are the second largest single category of collisions. The National Highway Traffic Safety Administration (NHTSA) has sponsored work in rear-end collision avoidance since 1992. Key results of this work were presented at the NHTSA-sponsored Johns Hopkins University Applied Physics Laboratory (JHU/APL) Rear-End Collision Avoidance Symposium (Reference 1). A rear-end collision warning system will typically contain three system elements: one or more sensors to collect critical information about an impending collision, a collision alert algorithm to process the information and determine whether a collision is imminent and an alert should be presented to the driver, and a driver-vehicle interface to present this information to the driver in a manner that elicits the appropriate collision avoidance actions.

Along with sponsoring work in the rear-end collision avoidance area, NHTSA developed an experimentally based rear-end collision warning algorithm (Reference 2) and sponsored analysis of the warning algorithm by Mitretek using field operational test data (Reference 3) collected during the Intelligent Cruise Control Field Operational Test. JHU/APL, building upon this previous work, has developed for NHTSA an algorithm that alerts drivers to potentially dangerous driving situations and the need to take evasive action. This NHTSA Algorithm has been integrated, along with a General Motors (GM)-developed algorithm, into a prototype collision warning system developed by GM for the Automotive Collision Avoidance System (ACAS) Field Operational Test (FOT). The ACAS FOT is being conducted as part of a 5-year cooperative research agreement between NHTSA and GM to develop and field test a limited fleet of vehicles equipped with an adaptive cruise control system and a prototype rear-end collision warning system.

The NHTSA Algorithm uses the host vehicle velocity and acceleration, along with the collision warning system-supplied values for range, range rate, and relative acceleration of the lead vehicle, to calculate a miss distance between the host and lead vehicles at 0.1-s intervals. The miss distance is the closest distance that occurs between the two vehicles if the driver of the host vehicle initiated braking, after a delay time, at a designated host vehicle maximum braking capability. This calculated distance is compared to a miss-distance threshold, and if it is less, an alert is provided to the driver. The algorithm accounts for a driver sensitivity setting and includes a look-ahead calculation to determine if the threshold would be passed before the next time interval. The performance of the algorithm has been examined against designated operational scenarios. These scenarios include cases of a constant speed host vehicle encountering a stopped lead vehicle, a

constant speed host vehicle encountering a constant but slower speed lead vehicle, and a constant speed host vehicle encountering a lead vehicle braking from the same initial speed.

The NHTSA Algorithm provides four alert levels. The lowest level corresponds to "no alert." The highest level is an "imminent collision" alert, for which the miss distance is calculated using an assumed host vehicle maximum braking capability. Two cautionary alert levels provide early warning of collisions based on the host vehicle braking at reduced levels. A driver-set, three-level warning sensitivity parameter scales the braking capability used by the algorithm for the cautionary alerts.

1.2   PURPOSE

The purpose of this report is to document the algorithm developed by JHU/APL for NHTSA under the NHTSA Alert Algorithm Development Program from October 1999 through June 2002. This report will describe the theory of operation of the NHTSA Algorithm, its theoretical performance under a set of defined operational scenarios, its measured performance when installed in a test vehicle with a prototype collision warning system, and its performance as evaluated by a simulation conducted to determine a system probability of collision.

1.3   ORGANIZATION OF DOCUMENT AND TERMS

This document is divided into an executive summary and six sections. Following this introductory section, Section 2 describes the theory of operation of the NHTSA Algorithm. Section 3 presents a theoretical analysis of the performance of the algorithm for defined operational scenarios. Section 4 provides the results of testing of the alert algorithm when installed in a test vehicle with a prototype collision warning system. Section 5 presents the results of a simulation of the algorithm operation conducted to determine a system probability of collision for an example scenario. Section 6 presents summary observations.

The terms *NHTSA Alert Algorithm*, *NHTSA Algorithm*, *Alert Algorithm*, *alert algorithm*, and *algorithm* may be used interchangeably in this document to refer to the alert algorithm developed for NHTSA under the NHTSA Alert Algorithm Development Program.

Section 2

ALGORITHM DESCRIPTION

2.1   <u>INTRODUCTION</u>

The objective of the NHTSA Algorithm is to issue collision alerts that allow the driver of the host vehicle to stop or approach no closer than a designated distance behind a stopped or decelerating lead vehicle. The decision to issue an alert is made every 100 ms upon parameter update by the collision warning system. The algorithm computes the projected miss distance at each parameter update interval based on an assumed constant host vehicle deceleration and estimates of host and lead vehicle speed and acceleration and the range between the vehicles. This projected miss distance is then compared with a miss-distance threshold to determine if a warning should be issued.

The NHTSA Algorithm provides four alert levels. The lowest level corresponds to "no alert." The highest level is an imminent collision alert, for which the miss distance is calculated using an assumed host vehicle maximum braking capability. In addition, two cautionary alert levels provide early warning of collisions based on the host vehicle braking at reduced levels. A driver-set, three-level warning sensitivity parameter modifies the braking capability used by the algorithm for the cautionary alerts.

The miss-distance threshold has a fixed component and a variable component that is a function of the host vehicle speed. The variable component is based on a "look ahead" of one parameter update interval to ensure that the fixed component would not be violated before the next set of parameters is received. Alerts are issued when the calculated miss distance is less than the threshold miss distance in two of the last three time intervals for an alert level. An alert may be suppressed based on conditions such as the host-vehicle speed being below a threshold level or while the vehicle is braking. Once an alert is issued, the alert level is normally maintained for a minimum of 1 s or while the range between the two vehicles is closing, unless a higher alert level is issued. An alert may be cleared or reduced if the current target is dropped and replaced by a new target vehicle.

2.2   <u>BACKGROUND</u>

This section discusses the assumptions upon which the algorithm was developed, the input parameters used by the algorithm, and other algorithm parameters. These are summarized in Table 2-1. The following assumptions and design decisions were implicit in the development of the algorithm:

    a. The current input parameter values represent the best available estimates and are stable and accurate.

    b. The lead vehicle will maintain its current deceleration.

2-1

c. The host vehicle will maintain its current acceleration for a fixed reaction time and then decelerate at a constant, prescribed level.

d. Alerts are inhibited when the host vehicle velocity is below a threshold value.

e. Alerts are inhibited for oncoming (including backing) vehicles.

f. The standard mode collision alert is based on a miss distance calculated using an assumed host vehicle maximum braking capability.

g. Situations where the host vehicle is closely following the lead vehicle are handled by a special tailgating mode of operation.

h. Situations where the vehicle's Adaptive Cruise Control (ACC) system is turned on and actively tracking a lead vehicle are handled by a special ACC mode of operation.

The following input parameters are required by the NHTSA Algorithm at each parameter-sampling (time) interval:

a. Host Vehicle Velocity (V_H)

b. Host Vehicle Acceleration (A_H)

c. Range (R)

d. Range Rate (RR)

e. Relative Acceleration (A_R)

f. Lead Vehicle Velocity (V_L) (calculated as the sum of V_H and RR)

g. Lead Vehicle Acceleration (A_L) (calculated as the sum of A_H and A_R)

Table 2-1 NHTSA Algorithm Features

Operating Modes:	
Standard	Used for normal driving situations Based on a calculated miss distance
Tailgating	Used when closely following the lead vehicle Based on range and lead vehicle braking
ACC	Used in conjunction with ACC subsystem of ACAS FOT Collision Warning System
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Range Rate	Supplied by collision warning system
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Time Interval	Input parameters updated and calculations made every 100 ms
Reaction Time	Driver and system delay of 1.5 s (0.5 s when brake applied)
Assumed Maximum Braking Level	Imminent alert miss-distance calculations use 0.55 g, varies by warning sensitivity level for cautionary alerts
Warning Sensitivity Level	Three levels - Near, Mid, Far (aggressive to conservative drivers) used to modify braking level for cautionary alerts
Brake Applied	Supplied by host vehicle
ACC State	Supplied by ACC subsystem of collision warning system
Miss-Distance Threshold	A fixed 2-m component plus a time-interval look ahead component
Alert Levels	No alert, two levels of cautionary alerts (early and intermediate), and imminent crash alert
Alert Suppression	Oncoming vehicles, host vehicle velocity below threshold

The NHTSA Algorithm uses the following additional variables or constants:

a. Reaction Time (T_R) – This time, which accounts for the driver reaction time and system delay time that occur prior to full application of vehicle braking after a warning is issued, is normally set to 1.6 s. This represents a desired value of 1.5 s plus 0.1 s to account for the requirement that the miss-distance threshold must be exceeded in two of the last three time intervals. If the "Brake Applied" variable is "On," indicating that the driver has applied the brake, T_R is set to 0.5 s.

b. Assumed Host Vehicle Maximum Braking Capability (A_{Hmax}) – This value is currently set to -0.55 g. The A_{Hmax} used to determine the miss distances for the

cautionary alert levels is reduced and varies by the driver-set Warning Sensitivity.

c. Warning Sensitivity – This variable may be set to one of three levels (Near, Mid, or Far) by the driver. It is expected that a more aggressive driver would choose the Near sensitivity level, which implies a desire for shorter headways between the host and lead vehicles, and that the most conservative drivers would choose the Far sensitivity level, which implies a desire for longer headways.

d. Brake Applied – This variable indicates the brake has been applied by the driver (On condition). For the ACAS FOT, the GM Extended Brake signal was used.

e. Target Type– The ACAS FOT collision warning system identifies valid targets as the Closest In-Path Moving Vehicle (CIPV), the Closest In-Path Stationary Object (CIPS), or as a Moving Vehicle Projected to Enter the Host Vehicle's Path (PIHP).

f. Target Number - As targets enter the system they are assigned an available target number in the range of 1 to 15.

g. ACC State – This variable provides information on the status of the ACAS FOT ACC system. It is decoded to provide three status indications:

    (1) ACC Active – This variable indicates whether the ACC system is On or Off.

    (2) ACC Vehicle Ahead – This variable indicates whether the ACC system is actively tracking a lead vehicle.

    (3) ACC Alert – This variable, in combination with ACC Active and ACC Vehicle Ahead, indicates that the ACC system's braking capability is exceeded.

The GM Collision Warning System for the ACAS FOT provides input parameters for multiple targets. These are designated as the CIPV, the CIPS, and potential multiple PIHPs. The NHTSA Algorithm processes data for CIPV and CIPS targets; PIHP targets are not currently processed. When both CIPV and CIPS targets are present, the NHTSA Algorithm estimates a time to collision as R divided by RR and processes the target with the shorter time to collision.

The NHTSA Algorithm assumes that the targets provided to it are actual targets in the path of the host vehicle; there is no attempt made by the algorithm to verify if the targets presented to it are valid. Currently, because of noise the NHTSA Algorithm filters the host vehicle acceleration parameter available from the collision warning system using an adaptive time-constant exponential filter, as shown in Figure 2-1.
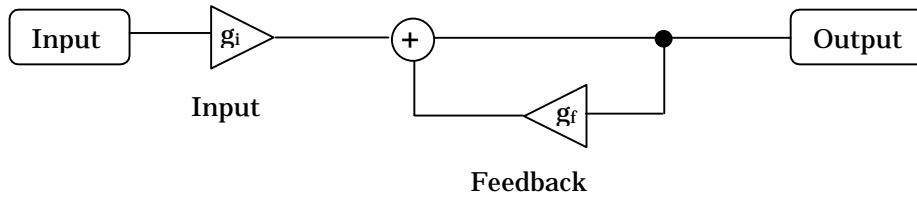
Figure 2-1 Adaptive Time Constant Filter

The filter time constant is controlled by the differences between successive A_H measurements; this detects trends in the signal by identifying large or consistent changes in one direction or the other. When a "signal changing" condition is detected, the time constant is reduced. The input coefficient (g_i) of the filter is set to the absolute value of 0.4 times the sum of the five latest changes in A_H measurements:

$$g_i = |0.4 *[\Delta AH(0) + \Delta AH(-1) + \Delta AH(-2) + \Delta AH(-3) + \Delta AH(-4)]|, \tag{2-1}$$

with the constraint

$$0.1 \le g_i \le 1. \tag{2-2}$$

The feedback coefficient (g_f) is set to 1 minus the input coefficient:

$$g_f = 1 - g_i. \tag{2-3}$$

When the input coefficient is 1, the input is accepted without filtering. A slow filter response occurs when small input coefficients are in effect. The input coefficient lower limit of 0.1 prevents bias errors from persisting when A_H is constant.

2.3   STANDARD MODE MISS-DISTANCE EQUATIONS

The standard operating mode of the NHTSA Algorithm bases the decision to issue a collision alert on a miss distance calculated using an assumed host vehicle maximum braking capability. There are three basic cases that must be considered in the calculation of miss distance: an initially moving lead vehicle stops prior to the host vehicle, the host vehicle stops while the lead vehicle is still in motion, or the lead vehicle is initially stopped. The calculation of miss distance varies by the case. To determine the case that applies, the time for the lead vehicle to stop (T_{LS}) and the time for the host vehicle to stop (T_{HS}) are calculated as follows and compared:

$$T_{LS} = -V_L/A_L, \tag{2-4}$$

and

$$T_{HS} = T_R - (V_H + A_H T_R)/A_{Hmax}. \tag{2-5}$$

2-5

An exception to the standard calculation of T_{HS} occurs if the host velocity at T_R (i.e., $V_H + A_H T_R$) is projected to be negative, which would result in the host vehicle stopping prior to T_R. In this case T_{HS} is calculated as

$$T_{HS} = -V_H / A_H. \tag{2-6}$$

When an initially moving lead vehicle comes to a stop prior to the host vehicle, the miss distance (D_{miss}) between the vehicles will occur when the host vehicle comes to a stop. This case can be divided into three segments depending on the relationship between T_{LS} and T_R. When $T_{LS} \geq T_R$, these segments are from the present time through the host vehicle reaction time ($t = 0$ to T_R), from the host vehicle reaction time until the lead vehicle stops ($t = T_R$ to T_{LS}), and the time from when lead vehicle stops until the host vehicle stops ($t = T_{LS}$ to T_{HS}). When $T_{LS} < T_R$, these segments are from the present time until the lead vehicle stops ($t = 0$ to T_{LS}), the time from when lead vehicle stops through the host vehicle reaction time ($t = T_{LS}$ to T_R), and the time from the host vehicle reaction time until the host vehicle stops ($t = T_R$ to T_{HS}). This miss distance is calculated as

$$D_{miss} = R + \Delta R1 + \Delta R2 + \Delta R3. \tag{2-7}$$

Where for the case $T_{LS} \geq T_R$,

$$\Delta R1 = (RR)T_R + \tfrac{1}{2}(A_L - A_H)(T_R)^2. \tag{2-8}$$

$$\Delta R2 = (RR + (A_L - A_H)T_R)(T_{LS} - T_R) + \tfrac{1}{2}(A_L - A_{Hmax})(T_{LS} - T_R)^2. \tag{2-9}$$

$$\Delta R3 = [RR + (A_L - A_H)T_R + (A_L - A_{Hmax})(T_{LS} - T_R)](T_{HS} - T_{LS})$$

$$+ \tfrac{1}{2}(0 - A_{Hmax})(T_{HS} - T_{LS})^2. \tag{2-10}$$

Equations 2-7 to 2-10 simplify to

$$D_{miss} = R + \tfrac{1}{2}(A_H - A_{Hmax})(T_R)^2 - \tfrac{1}{2}A_L(T_{LS})^2 - (A_H - A_{Hmax})T_R T_{HS} + (RR)T_{HS}$$

$$+ A_L T_{HS} T_{LS} - \tfrac{1}{2}A_{Hmax}(T_{HS})^2. \tag{2-11}$$

When $T_{LS} < T_R$, Equations 2-8 to 2-10 are set up similarly and also simplify to Equation 2-11.

When either the lead vehicle is initially stopped or the host vehicle comes to a stop first (which includes constant lead vehicle velocity scenarios), the miss distance between the vehicles can be determined from only two segments and occurs when the range rate equals zero. The two segments are from the present time through the host vehicle reaction time ($t = 0$ to T_R) and from the host vehicle reaction time until the miss distance occurs ($t = T_R$ to T_M). The range rate at time $t = T_M$ is calculated as

$$RR_{TM} = 0 = [RR + (A_L - A_H)T_R] + (A_L - A_{Hmax})(T_M - T_R), \tag{2-12}$$

which yields

$$T_M = \{[RR + (A_L - A_H)T_R]/(A_{Hmax} - A_L)\} + T_R. \tag{2-13}$$

An exception to the standard calculation of T_M occurs if T_M is calculated to be less than T_R. In this case T_M is set to T_R. This is done to avoid potential false alarms in situations when the RR projected to T_R is positive and the host vehicle "outbrakes" the lead vehicle after T_R. Standard processing in this case would calculate a past time and reduced value for the miss distance between the vehicles.

The miss distance is calculated as

$$D_{miss} = R + \Delta R1 + \Delta R2. \tag{2-14}$$

Where,

$$\Delta R1 = (RR)T_R + \tfrac{1}{2}(A_L - A_H)(T_R)^2. \tag{2-15}$$

$$\Delta R2 = [RR + (A_L - A_H)T_R](T_M - T_R) + \tfrac{1}{2}(A_L - A_{Hmax})(T_M - T_R)^2. \tag{2-16}$$

Equations 2-11 to 2-13 simplify to

$$D_{miss} = R + (RR)T_M + \tfrac{1}{2}(A_L - A_{Hmax})(T_M)^2 - (A_H - A_{Hmax})T_M T_R$$

$$+ \tfrac{1}{2}(A_H - A_{Hmax})(T_R)^2. \tag{2-17}$$

An exception to the standard method of determining whether Equation 2-11 (lead vehicle stops first) or 2-17 (host vehicle stops first) is used for determining D_{miss} occurs when A_L is greater than or equal to -1 m/s². In this case, Equation 2-17 is always used to calculate D_{miss}. This is done because lead vehicles that are holding speed or accelerating should not stop before the host vehicle; the value of -1 m/s² provides a margin to cover "noisy" input parameter values. The implementation of the NHTSA Algorithm also includes precautions to avoid divide-by-zero errors. Denominators whose absolute magnitudes are less than 0.001 are replaced with the value of +0.001. This is done in the calculations of T_{LS}, T_{HS}, and T_M.

2.4 ALERT GENERATION AND RELEASE

The decision to issue an alert in the standard mode is based on a miss-distance threshold being passed in two of the last three time intervals for the current target vehicle. The determination of the target threshold being passed in two of the last three time intervals is restarted when the target number changes. An alert may be suppressed by one of a number of conditions discussed below. Once a standard mode alert is issued, it is kept on for a minimum of 1 s unless a higher alert level is required or the target vehicle changes. After 1 s the alert level may go to a lower level or be cleared, when the RR becomes greater than -1.99 m/s or when the current range becomes equal to or greater than 2.5 m plus the host vehicle velocity times the time interval (Equation 2-18). The RR test is meant to determine that the rate of closure is no longer dangerous. The value of -1.99 m/s provides a margin to cover "noisy" input parameter values.

$$R_{current} \geq 2.5 \text{ m} + (V_H)(0.1 \text{ s}). \tag{2-18}$$

The operation of the alert generation logic can be interfered with by the assignment of multiple target numbers to different reflection points on a single vehicle and the switching

between these target numbers at close ranges by the collision warning system. A modification has been made to the algorithm to prevent this from occurring. This modification results in two changes to the alert generation process when the target range is (1) less than 17.001 m, (2) the change in range since the last time tick is less than 1.001 m, and (3) the change in range rate since the last time tick is less than 0.5001 m/s. The first is the determination of the target threshold being exceeded in two of the last three time intervals is not restarted when the target number changes. The second is an alert is not cleared on a target number change.

The tailgating mode discussed below independently issues tailgating mode alerts. The overall alert level output by the system is the highest alert level produced by either the standard or tailgating mode.

2.4.1 MISS-DISTANCE THRESHOLD

The miss-distance threshold (D_{thresh}) to which the projected D_{miss} for each target vehicle at each time interval is compared has a fixed component of 2 m and a variable component that is a function of the host vehicle speed. The variable component is based on a "look ahead" of one time interval to ensure that the fixed component would not be violated before the next set of parameters is received. This look ahead is computed as V_H times the time interval. Thus, the miss-distance threshold is calculated as

$$D_{thresh} = 2 \text{ m} + (V_H)(0.1 \text{ s}). \tag{2-19}$$

2.4.2 MULTIPLE ALERT LEVELS

The NHTSA Algorithm provides three alert levels in addition to a "no alert" level. The highest of the three levels is an imminent collision alert for which the miss distance is calculated using an assumed host vehicle maximum braking capability. Two cautionary alert levels (early and intermediate) are based on the host vehicle braking at reduced levels. The cautionary alert braking levels vary depending on the driver-set Warning Sensitivity level. The assumed host vehicle-braking levels used by the algorithm are given in Table 2-2. The algorithm uses these host vehicle-braking levels to calculate three miss distances in parallel, one for each level of warning.

Table 2-2 Assumed Host Vehicle Maximum Braking Capability

Warning Sensitivity	Assumed Host Vehicle Maximum Braking Capability (g)		
	Alert Level		
	Early	Intermediate	Imminent
Near	0.38	0.45	0.55
Mid	0.32	0.40	0.55
Far	0.27	0.35	0.55

2.4.3   ALERT SUPPRESSION

Alerts may be suppressed if certain conditions are met. The NHTSA Algorithm has four alert suppression conditions:

a. Low Host Vehicle Velocity

b. Oncoming Lead Vehicle

c. While Braking

d. When Passing

These conditions are meant to suppress alerts in situations where it is believed that the collision warning system would provide undesired alerts to the driver. The NHTSA Algorithm implements the low host vehicle velocity condition by suppressing alerts until V_H reaches 11.199 m/s; once this threshold velocity is reached, alerts are not suppressed because of low host vehicle velocity until V_H goes below 9.199 m/s. The oncoming lead vehicle suppression condition is implemented by suppressing alerts for lead vehicles with V_L less than -4.99 m/s. The value of -4.99 m/s provides a margin to cover "noisy" input parameter values. The while braking suppression condition prevents cautionary alerts from being issued while the Brake Applied On signal is active; it does not affect the issuing of imminent alerts. Alerts are also suppressed when the driver accelerates significantly, as in a passing situation. The alert suppression occurs for $A_H > 0.8$ m/s² at a V_H of 20 mph. The threshold decreases linearly to 0.4 m/s² at a V_H of 60 mph and remains constant at that level for $V_H > 60$ mph.

2.5   <u>TAILGATING MODE OPERATION</u>

The reason for implementing a tailgating mode is that the standard mode can allow a host vehicle to gradually approach to within 5 m of a lead vehicle without issuing any level of alert. This is considered to be undesirable from a safety perspective and because of the potential sensitivity of the algorithm to sensor noise at these short ranges. The tailgating mode is not enabled unless the ACC system is off; specified conditions are met for R, RR, and V_H; and there is a valid, constant radar target. It is disabled when the ACC system is on because close proximity warnings are not needed when the ACC system is actively controlling the vehicle throttle and brakes.

The range condition is met when R becomes less than the mode enable turn-on range given in Table 2-3 for the current Warning Sensitivity level; once this threshold is passed, the range condition is met until R exceeds the turn-off range given in Table 2-3. The range rate condition is met once RR enters the range of –7.001 to +1.999 m/s; once this range is entered, the range rate condition is met until RR becomes less than –7.701 m/s or greater than 2.699 m/s. The host vehicle velocity condition is met when V_H exceeds 11.199 m/s (25 mph); once this threshold is passed the host vehicle velocity condition is met until V_H goes below 9.199 m/s. Also, once the range or range rate condition is met, a hold is applied that keeps these conditions enabled as long as the condition is met for any of the last three time intervals. This compensates for a small amount of radar target number switching.

Table 2-3 Tailgating Mode Alert Ranges

Warning Sensitivity	Tailgating Mode Enable & Alert Ranges (m)					
	Mode Enable		Early Alert		Intermediate Alert	
	Turn-On	Turn-Off	Turn-On	Turn-Off	Turn-On	Turn-Off
Near	≤25	>26	≤15	>16	≤10	>11
Mid	≤27	>28	≤20	>21	≤12	>13
Far	≤30	>31	≤25	>26	≤16	>17

The valid radar target condition is met by having a CIPV target designated by the radar system, while the constant target condition is handled by tracking the target number presented by the radar system at each time interval. Each of the 15 possible target numbers is tracked using an up-down counter with limits at zero and eight. The counter for the presented target number is incremented at each time interval, while the counters for the other 14 target numbers are decremented. When the counter for the current target number reaches five, the constant target condition is passed until the count falls to three. Once this condition is met, a hold is applied that keeps this condition enabled as long as the condition is met for any of the last three time intervals. The counters are cleared to zero upon the issuing of a standard mode alert that exceeds the tailgating mode alert.

The previously noted assignment of multiple target numbers to different reflection points on a single vehicle, and the switching between these target numbers at close ranges by the collision warning system can interfere with the determination of the constant target condition. To prevent this from occurring, the target number presented to the target number tracking function previously described is not changed when the target range is less than 17.001 m, the change in range since the last time interval is less than 1.001 m, and the change in range rate since the last time interval is less than 0.5001 m/s.

The cautionary alerts are activated when R becomes less than the turn-on range thresholds given in Table 2-3 for the current Warning Sensitivity level; once a threshold is passed, the alert remains on until R exceeds the turn-off range given in Table 2-3. The thresholds were based on ranges supporting lead vehicle braking of -0.25 g responded to by host vehicle braking of -0.3 and -0.4 g, adjusted by engineering judgment from operation of the collision warning system. The 1-s minimum and RR holds applied to standard mode alerts are not applied to tailgating mode alerts.

The tailgating mode imminent alert is not range dependent but is designed to provide immediate warning that the lead vehicle is braking. Tailgating mode imminent alerts are issued under two conditions. The first is when A_R is less than -2.49 m/s². The second is when a four-point moving average of the derivative of RR is less than -1.875 m/s²; this is intended to overcome delay in A_R because of radar system Kalman filtering of this parameter.

The derivative of RR is calculated as

$$RR9(t_1) = [RR(t_1) - RR(t_0)]/0.1 \text{ s} \tag{2-20}$$

While the four-point moving average of the derivative of RR is

$$RR9_{AVG}(t_3) = [RR9(t_3) + RR9(t_2) + RR9(t_1) + RR9(t_0)]/4 \qquad (2\text{-}21)$$

The 1-s minimum and RR holds applied to standard mode imminent alerts are not applied to tailgating mode imminent alerts. The tailgating mode issues alerts independently of the standard mode. The overall alert level output by the system is the highest alert level produced by either the standard or tailgating mode.

2.6 ACC MODE OPERATION

When the vehicle's ACC system is turned on (indicated by ACC Active) the NHTSA Algorithm will continue its normal operation with three exceptions. First, tailgating mode is disabled because proximity warnings are not needed when the ACC system is actively controlling the vehicle. Second, when the ACC system is actively tracking a lead vehicle (indicated by ACC Active and ACC Vehicle Ahead), cautionary alerts are not issued. Third, when the ACC system is actively tracking a lead vehicle, imminent alerts are only issued for CIPV targets when the ACC system reports that its braking capability is exceeded (indicated by ACC Active, ACC Vehicle Ahead, and ACC Alert). Because the ACC system does not operate with stationary targets, relying on the ACC system reporting that its braking capability is exceeded to issue any imminent alert would result in not issuing alerts for stopped targets. Thus, the NHTSA Algorithm continues its normal imminent collision warning process for targets with $V_L < 4.47$ m/s, even when the ACC system is on.

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Section 3

ALGORITHM ANALYSES

3.1   INTRODUCTION

This section presents two sets of theoretical analyses of the performance of the NHTSA Algorithm. The first analysis determines the performance of the algorithm under the assumption of perfect input data. This is done for three operational scenarios representing the pre-crash conditions for many of the rear-end collisions that the collision warning system is meant to prevent. The second analysis examines the effects of measurement noise and driver variability on algorithm performance. The objective of these analyses is to provide an understanding of algorithm performance in a perfect environment with no noise and under the conditions of noisy input measurements and driver variability, prior to examining its performance when installed in a vehicle equipped with a prototype collision warning system.

3.2   OPERATIONAL SCENARIOS

Three operational scenarios, representative of the pre-crash conditions for many rear-end collisions, were used to examine the performance of the algorithm under the assumption of perfect input data. Algorithm performance is expressed as the range at which an imminent alert would be given. These scenarios are as follows:

a. Stopped Lead Vehicle Scenario – The host vehicle is driving at a constant speed and encounters a stopped lead vehicle in its path of travel. According to GES data from 1992 to 1996 (Reference 4), 33 percent of rear-end collisions occur when a constant speed host vehicle crashes into a stopped lead vehicle. Host vehicle speeds of 30 to 65 mph are examined in this analysis.

b. Slower Lead Vehicle Scenario – The host vehicle is driving at a constant speed and encounters a lead vehicle driving at a constant but slower speed in its lane of travel. The GES data indicate that 15 percent of rear-end collisions occur under these conditions. The analysis examines lead vehicle speeds of 5 to 45 mph for a host vehicle speed of 50 mph.

c. Braking Lead Vehicle Scenario – The host vehicle and the lead vehicle are driving at the same initial speed, and then the lead vehicle suddenly brakes. According to the GES data, 38 percent of rear-end collisions occur when two vehicles are driving at the same speed and the host vehicle strikes the lead vehicle as the lead vehicle is braking. The analysis examines lead vehicle braking of -0.3 g for an initial host and lead vehicle speed of 60 mph, with the initial range between the host and lead vehicle varied from 25 m to 150 m.

3.3 OPERATIONAL SCENARIO PERFORMANCE

The stopped lead vehicle scenario examines the performance of the algorithm when a host vehicle at constant speed encounters a stopped lead vehicle. Figure 3-1 presents the algorithm performance for host vehicle speeds of 30 to 65 mph. As expected, a larger host vehicle velocity requires a longer alert range to stop the vehicle before a collision will occur. The alert range increases from 40 m at 30 mph to 127 m at 65 mph. These alert ranges are theoretical and may not be supported by the operation of a collision warning system radar at higher host vehicle speeds or on curved roads. For example, it is possible that the required imminent alert at a range of about 127 m for a vehicle driven at 65 mph would not be given because of the target being outside the detection range of a collision warning system radar, even when on a straight, flat road.

Figure 3-2 presents the imminent alert warning ranges for the slower lead vehicle scenario. This is done for a host vehicle speed of 50 mph and lead vehicle speeds of 5 to 45 mph. As expected for a constant host vehicle speed, the alert range increases as the lead vehicle speed decreases. The alert range increases from less than 10 m at a lead vehicle speed of 45 mph to greater than 70 m at a lead vehicle speed of 5 mph. A host vehicle encountering a relatively slow lead vehicle needs a greater warning range to stop before a collision than when the lead vehicle speed is closer to the host vehicle speed.

The performance of the alert algorithm for the braking lead vehicle scenario is presented in Figure 3-3. The analysis assumes the host and lead vehicle have the same initial speed of 60 mph and that the lead vehicle brakes at -0.3 g. The initial range between the host and lead vehicle was varied from 30 m to 150 m. Initial ranges below 30 m are not shown because the tailgating mode would be active at these ranges. As expected, alerts are issued shortly after the lead vehicle brakes at the shorter initial ranges, while for longer initial ranges the alert is given farther after the lead vehicle brakes. The alert range is slightly less than the initial range at 30 m and approaches 100 m for initial vehicle spacing of 150 m. The larger initial ranges in Figure 3-3 may not be supported by a collision warning system radar for all scenarios.
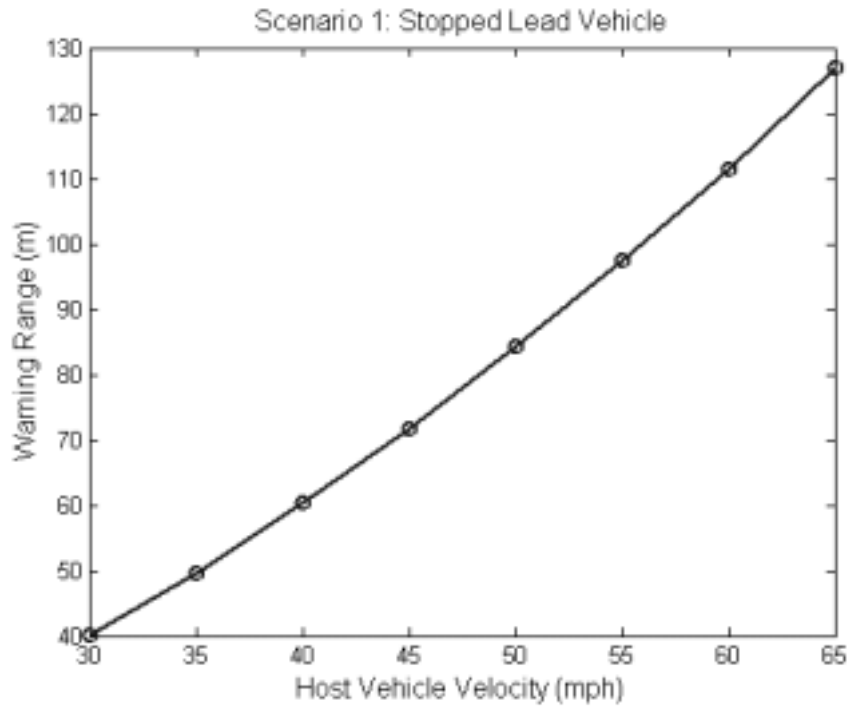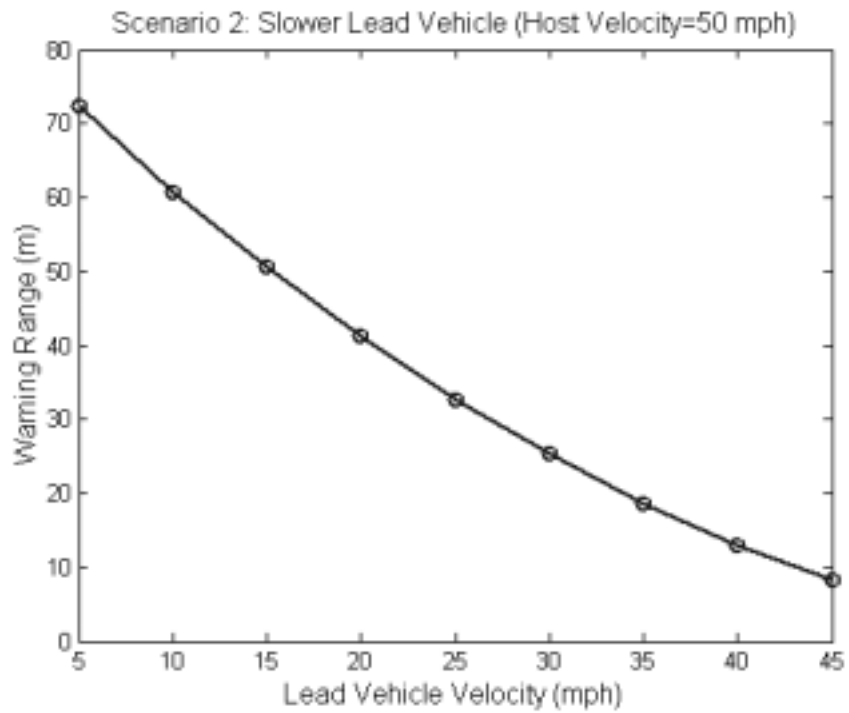
Figure 3-1 Stopped Lead Vehicle Scenario Performance

Figure 3-2 Slower Lead Vehicle Scenario Performance

3-3
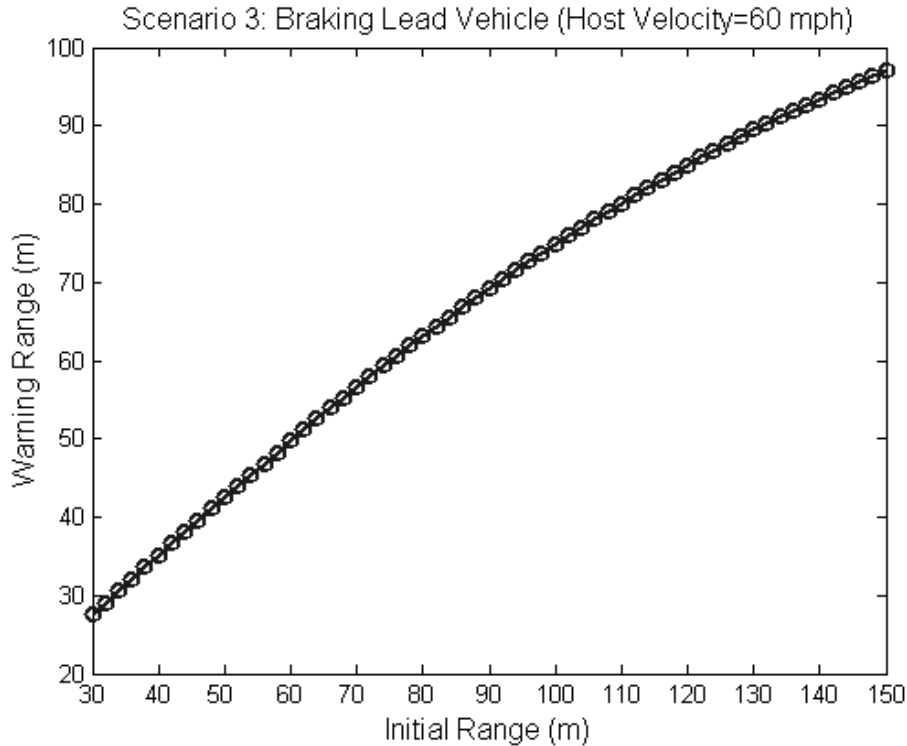
Figure 3-3 Braking Lead Vehicle Scenario Performance

3.4 <u>MEASUREMENT NOISE AND DRIVER VARIABILITY ANALYSIS</u>

Section 3.3 examined algorithm performance with the input parameters free of measurement noise. The analysis performed for this section examines algorithm performance when the input parameter measurements are noisy and the driver reaction varies.

The miss distance defined in Section 2.3 is a function of two sets of parameters:

$$D_{miss} = f(\mathbf{P}, \mathbf{Q}). \tag{3-1}$$

The input measurements are

$$\mathbf{P} = (A_H, V_H, R, RR, A_R), \tag{3-2}$$

and the assumed driver response is

$$\mathbf{Q} = (A_{Hmax}, T_R). \tag{3-3}$$

This analysis considers how measurement noise (in $\mathbf{P}$) and driver variability (in $\mathbf{Q}$) affect the calculated value of D_{miss}. The miss-distance threshold for this analysis is held constant at 2 m; the "look ahead" variable component of Equation 2-19 is not considered. The analysis compares the performance of the NHTSA Algorithm when it has as input, the noise-free input measurement -

$\mathbf{P}^{True}$ and the true driver response - $\mathbf{Q}^{True}$, to when the input is the noisy input measurement - $\mathbf{P}^{Noisy}$ and the estimated driver response - $\mathbf{Q}^{Est}$. The estimated driver response, $\mathbf{Q}^{Est}$, is set to $A_{Hmax,est}$ = -0.55 g and $T_{R,est}$ = 1.5 s.

3.4.1 ANALYSIS PROCEDURE

The analysis is a five-step procedure as follows:

a. Take 10,000 random draws of $\mathbf{P}^{True}$ and $\mathbf{Q}^{True}$. These are considered the "true" vehicle dynamics and driver response. For each random draw, calculate D_{miss}(True) for the noise-free input measurement and true driver response case as:

$$D_{miss}(\text{True}) = f(\mathbf{P}^{True}, \mathbf{Q}^{True}). \tag{3-4}$$

b. Take 10,000 random draws of noise:

$$\mathbf{N} = (N_{AH}, N_{VH}, N_R, N_{RR}, N_{AR}). \tag{3-5}$$

Set

$$\mathbf{P}^{Noisy} = \mathbf{P}^{True} + \mathbf{N}, \tag{3-6}$$

and

$$\mathbf{Q}^{Est} = (A_{Hmax,est,} T_{R,est}). \tag{3-7}$$

Then for each random draw, calculate D_{miss}(Actual) for the noisy input measurement and estimated driver response case as:

$$D_{miss}(\text{Actual}) = f(\mathbf{P}^{Noisy}, \mathbf{Q}^{Est}). \tag{3-8}$$

c. If $D_{miss}(\text{True}) \leq 0$ and $D_{miss}(\text{Actual}) \geq 2$, then increment the number of MISS.

d. If $D_{miss}(\text{True}) \geq 4$ and $D_{miss}(\text{Actual}) < 2$, then increment the number of FALSE_ALARM.

e. Calculate the overall MISS and FALSE_ALARM probabilities by averaging over all 10,000 trials.

3.4.2 DETAILS OF RANDOM DRAW

The analysis procedure requires that random draws be made of the input measurement noise, the true driver response, and the true input measurements. The input measurement noise is generated as independent, random variables with the distributions given in Table 3-1. Here, U[a, b] represents the uniform distribution in the interval from a to b, while $G(\mu, \sigma)$ represents the Gaussian distribution with mean μ and standard deviation σ:

$$f(x) = \frac{e^{-(x-\mu)^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}} .$$ (3-9)

All units are metric (m, m/s, and m/s²). These noise distributions were derived from a noise analysis of data collected from the prototype collision warning system in the Engineering Development Vehicle (EDV) developed under the ACAS FOT.

Table 3-1 Noise Distributions

Parameter	Noise Distribution
A_H	G(–0.07,0.17)
V_H	U[–0.15,+0.15]
R	G(0.4,0.025)
RR	U[–0.0625,+0.0625]
A_R	G(–0.6,0.1)

The true driver responses, $A_{Hmax,True}$ and $T_{R,True}$, are drawn independently of one another using the distributions in Figures 3-4 and 3-5. The distribution for $A_{Hmax,True}$, shown in Figure 3-4, is a truncated Gaussian distribution with mean –0.6 g , standard deviation of 0.1 g, minimum of –0.8 g, and maximum of –0.3 g. It was based on input from Wassim Najm of the Volpe National Transportation Systems Center.[1] The distribution for $T_{R,True}$ was derived from a Transportation Research Record report by Chang et al. (Reference 5). It is modeled in Figure 3-5 as a lognormal distribution with median 1.1 s and dispersion parameter 0.53. (The mean and standard deviation are 1.30 s and 0.74 s, respectively.)

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[1] E-mail from Wassim G. Najm, Volpe National Transportation Systems Center, to Jack Ference, National Highway Traffic Safety Administration, "Thoughts on the MOE Program," 7 February 2001.
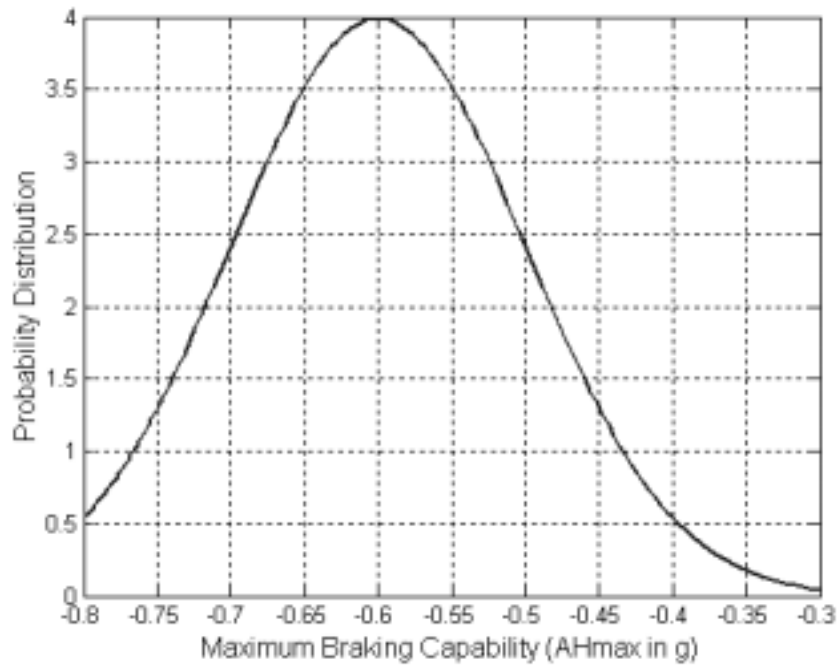
Figure 3-4 Host Vehicle Braking Distribution
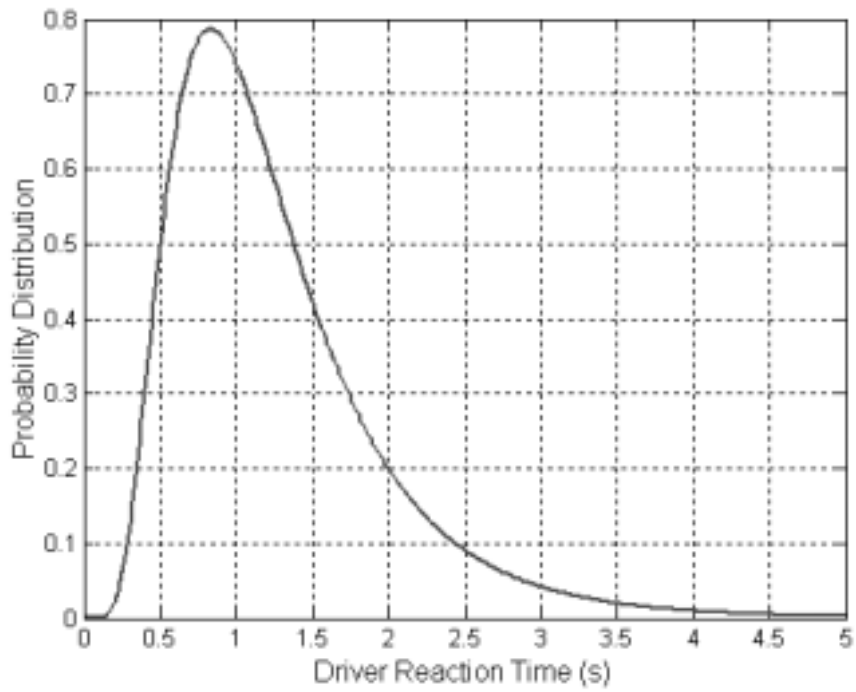

Figure 3-5 Reaction Time Distribution

The true input measurements are drawn using the distributions in Table 3-2. The distributions used vary as to whether the host vehicle is approaching a stopped lead vehicle or the lead vehicle is braking hard. L(μ,σ) represents the Laplacian distribution with mean μ and standard deviation σ :

$$f(x) = \frac{e^{-\sqrt{2}|x-\mu|/\sigma}}{\sqrt{2\sigma^2}}. \tag{3-10}$$

Again, all units are metric (m, m/s, and m/s²). The Laplacian distributions used for the host and lead vehicle acceleration are derived from the results presented in Reference 6.

Table 3-2 True Input Measurement Distributions

True Parameter	Vehicle Situation	
	Host Vehicle Approaches "Stopped" Lead Vehicle	Lead Vehicle Brakes "Hard"
A_H	L(0,0.3)	L(0,0.3)
V_H	U[20,30]	U[20,30]
R	U[60,80]	U[20,40]
RR	U[$-V_H$, $-V_H$ +5]	U[$-V_H$ +20, $-V_H$ +30]
A_R	L($-A_H$,0.3)	L($-5-A_H$,0.3)

3.4.3   PERFORMANCE ANALYSIS

The results of the analysis are given in terms of the Probability of False Alarm (PFA) versus the Probability of a Miss (P_{miss}). A False Alarm is a situation where an imminent alert is issued to the driver when conditions did not warrant the alert. Conversely, a Miss is defined as a situation where an imminent alert is not issued when the true conditions indicate that an alert should be given. For this performance analysis, PFA is calculated as the number of trials where D_{miss}(True) is $\geq$ 4 m and D_{miss}(Actual) is < 2 m divided by the number of trials where D_{miss}(True) is $\geq$ 4 m. P_{miss} is calculated as the number of trials where D_{miss}(True) is $\leq$ 0 m and D_{miss}(Actual) is $\geq$ 2 m divided by the number of trials where D_{miss}(True) is $\leq$ 0 m.

Figure 3-6 presents system performance as curves of PFA versus P_{miss} for two scenarios. In the first scenario the host vehicle is approaching a stopped (or slowly moving) lead vehicle, while in the second scenario the lead vehicle brakes hard. The points on the curves are generated by varying the value taken by $A_{Hmax,est}$. In these curves, $A_{Hmax,est}$ takes on the values of –1.00 g, –0.95 g, –0.90 g,…, –0.3 g, starting from the upper-left corner. As $A_{Hmax,est}$ is increased (lighter assumed braking), the PFA is increased while P_{miss} is decreased. The fact that the two curves overlap implies that the two scenarios are equally dangerous. The NHTSA Algorithm with $A_{Hmax,est}$ =

-0.55 g and $T_{R,est}$ = 1.5 s operates at a PFA of 0.65 and a P_{miss} of 0.03 for the stopped lead vehicle scenario.
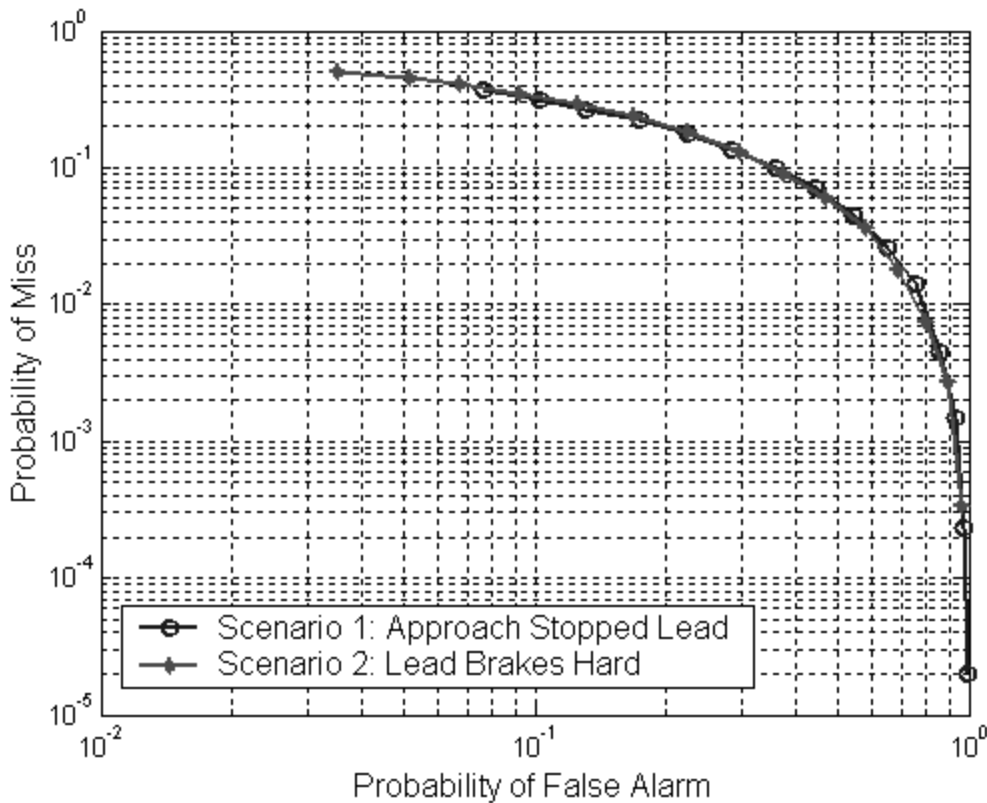
Figure 3-6 Algorithm Probability of False Alarm versus Probability of a Miss Performance

In Figure 3-6 the estimated driver reaction time was set at $T_{R,est}$ = 1.5 s. Additional analysis was performed to determine whether the system performance could be improved by varying $T_{R,est}$. The results of that analysis, shown in Figure 3-7, indicate that there is no improvement in performance by varying $T_{R,est}$. The curve marked by circles is the Scenario 1 curve from Figure 3-6 with $T_{R,est}$ fixed at 1.5 s and $A_{Hmax,est}$ varied. The curve marked by asterisks is the Scenario 1 curve with $A_{Hmax,est}$ fixed at -0.55 g and $T_{R,est}$ varied from 0.9 s to 2.3 s in increments of 0.2 s. The triangles represent all possible combinations of $T_{R,est}$ and $A_{Hmax,est}$. The fact that all three curves are the same implies that the performance curve is not affected by the choice of $T_{R,est}$ and/or $A_{Hmax,est}$. However, the choice of $T_{R,est}$ and $A_{Hmax,est}$ determines at which point on the performance curve the system operates.
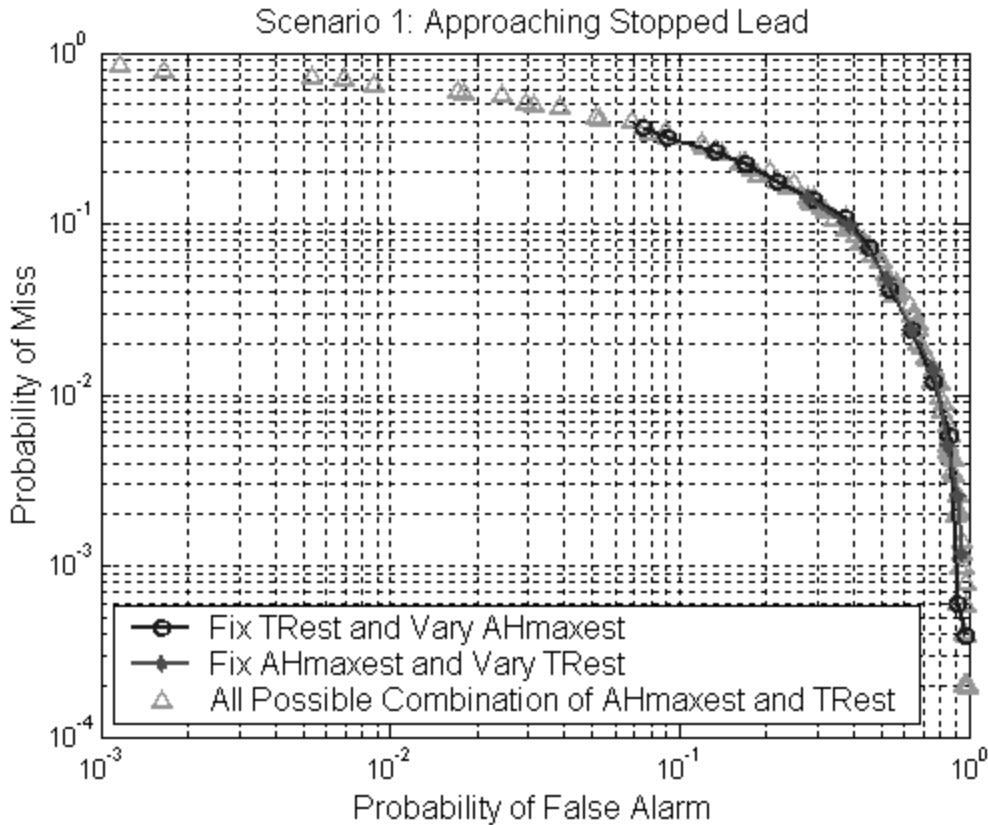
Figure 3-7 Algorithm Performance as Function of Estimated Driver Reaction Time and Braking Response

Analysis was also performed to determine whether measurement noise or error in estimating the driver response had a significant impact on algorithm performance. The results of this analysis are shown in Figure 3-8. The curve marked by triangles is for a deterministic true driver response ($T_{R,True}$ =1.5 s and $A_{Hmax,True}$ =-0.55 g in all cases). In this case the only variables affecting the performance are the measurement noises.

The curve marked by circles is for the case of no measurement noise. Here, performance is affected only by error in estimating the driver response. This curve overlaps the curve marked by asterisks, which is for the case of measurement noise and response error. These results indicate that error in estimating the driver response has a greater impact on algorithm performance than error in measuring the vehicle dynamics. The measurement noise has little effect on algorithm performance. These results agree with the results of a previous study by Kuchar (Reference 7).
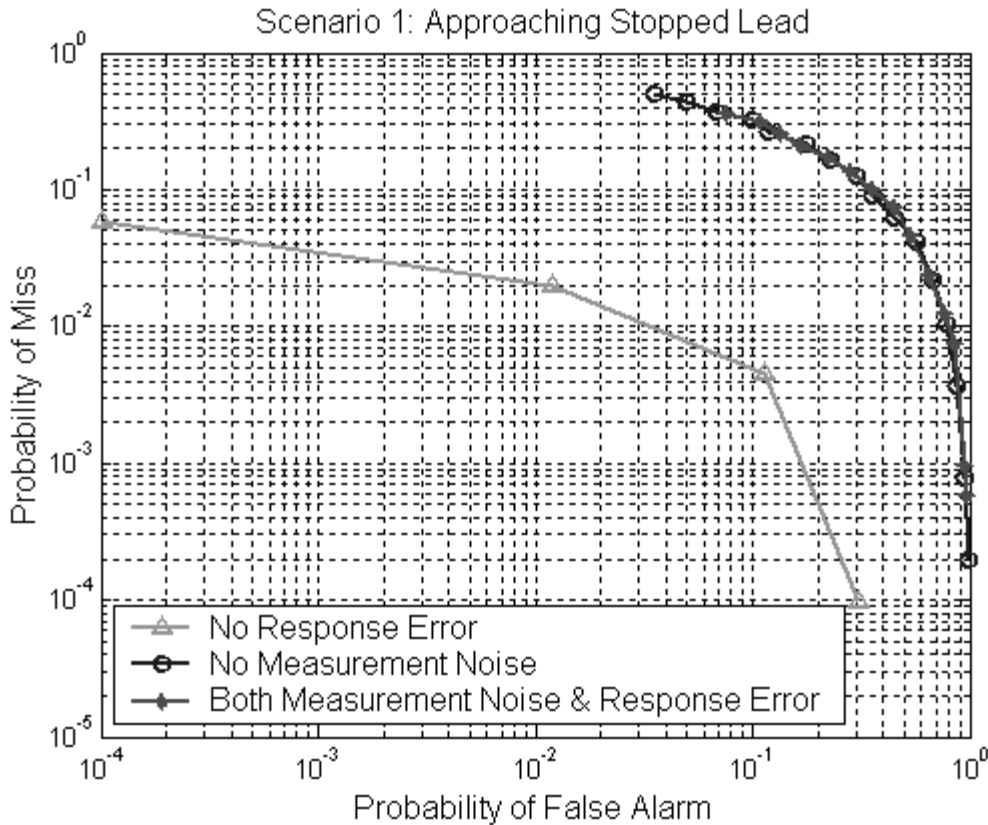
Figure 3-8 Algorithm Performance as Function of Driver Response Error and Measurement Noise

3.5 <u>PERFORMANCE SUMMARY</u>

Table 3-3 provides the theoretical imminent alert range of the NHTSA Algorithm as a function of host vehicle speed for three scenarios representing pre-crash conditions for many rear-end collisions. The stopped lead vehicle scenario shows a strong increase in alert range with increasing host vehicle speed. The slower lead vehicle scenario shows a strong increase in alert range with increasing host vehicle speed when the lead vehicle speed is kept constant at 10 mph. However, there is little difference in the alert range for increasing host vehicle speed when the difference in vehicle speeds is kept constant at 20 mph.

The braking lead vehicle scenario shows little difference in alert range when the host vehicle speed is increased for an initial range of 35 m. When the initial range is increased to 85 m, there is an increase in alert range with increasing host vehicle speed up to about 55 mph. This is expected, as alerts are issued shortly after the lead vehicle brakes at shorter initial ranges regardless of the host vehicle speed. For longer initial ranges, the alert is not given immediately after the lead vehicle brakes and the host vehicle speed may influence the timing of the alert.

Algorithm performance, in terms of PFA versus P_{miss}, is set by the choice of estimated driver reaction time and assumed host vehicle deceleration. The NHTSA Algorithm with $A_{Hmax,est}$ = -0.55 g and $T_{R,est}$ = 1.5 s, operates at a PFA of 0.65 and a P_{miss} of 0.03 for the stopped lead vehicle scenario. Analysis indicates that the error in estimating the driver response (braking level and reaction time) has a greater impact on the system performance than the error in measuring the vehicle dynamics, with the measurement noise having little effect on algorithm performance.

Table 3-3 NHTSA Algorithm Theoretical Imminent Alert Ranges in Meters

Scenario	Host Vehicle Speed				
	30 mph	40 mph	50 mph	60 mph	70 mph
Stopped Lead Vehicle	40 m	60 m	84 m	112 m	143 m
Slower Lead Vehicle [a]	24 m	25 m	25 m	25 m	26 m
Slower Lead Vehicle [b]	24 m	41 m	61 m	84 m	112 m
Braking Lead Vehicle [c]	30 m	31 m	31 m	31 m	32 m
Braking Lead Vehicle [d]	40 m [e]	56 m	63 m	66 m	67 m

[a]Lead vehicle 20 mph slower than host vehicle.

[b]Lead vehicle at constant speed of 10 mph.

[c]Same initial speed, -0.3 g braking, 35 m initial range.

[d]Same initial speed, -0.3 g braking, 85 m initial range.

[e]Lead vehicle comes to a stop prior to alert being issued.

Section 4

VEHICLE TESTING

4.1   <u>INTRODUCTION</u>

This section presents results of testing conducted with the NHTSA Algorithm installed in a test vehicle equipped with a prototype collision warning system. The testing included verification tests conducted on a test track and public road testing. The purpose of the public road testing was to obtain qualitative impressions from driving the test vehicle and to identify algorithm shortcomings that may not have been addressed in the selected verification tests. In addition, the effects of data quality on the performance of the algorithm are discussed.

4.2   <u>ALGORITHM VERIFICATION TESTS</u>

A subset of the verification tests developed for the ACAS FOT System was chosen to test the performance of the NHTSA Algorithm. The selected tests were specifically chosen to verify the performance of the algorithm itself and not that of the ACAS system as a whole. The following seven tests were chosen:

a.   Test 1 – The host vehicle is driving at a constant speed of 60 mph and encounters a stopped lead vehicle.

b.   Test 2 – The host vehicle is driving at a constant speed of 50 mph and encounters a lead vehicle driving at a constant speed of 10 mph.

c.   Test 3 – The host vehicle and the lead vehicle are driving at a speed of 60 mph with the host vehicle at a moderate distance behind the lead vehicle, and then the lead vehicle brakes hard (-0.3 g).

d.   Test 9 – The host vehicle and the lead vehicle are driving at a speed of 60 mph with the host vehicle tailgating the lead vehicle, and then the lead vehicle brakes moderately hard (-0.2 g).

e.   Test 15 – The host vehicle and the lead vehicle are driving at a speed of 40 mph with the host vehicle at a large distance behind the lead vehicle, and then the lead vehicle brakes very hard (-0.5 g).

f.   Test 20 – A lead vehicle traveling at 60 mph suddenly moves ahead of the host vehicle traveling at 50 mph.

g. Test 28 – The host vehicle traveling at an initial speed of 40 mph accelerates and passes a lead vehicle traveling at 40 mph.

The first five tests are representative of the major rear-end collision scenarios. For these tests the alert ranges from the verification test data are compared to the theoretical alert ranges based on the Algorithm Analysis of Section 3.2. Tests 20 and 28 are analyzed differently in that they are tests for the presence of nuisance alerts. A sample of trials from testing of the most recent version of the NHTSA Algorithm is presented here; other trials had similar performance.

4.2.1 TEST 1 – HOST VEHICLE ENCOUNTERS STOPPED LEAD VEHICLE

In this verification test the host vehicle is traveling on a straight, flat road at 60 mph and approaches a lead vehicle stopped ahead in the same lane. Two trials were performed on 27 September 2001. This test has a theoretical imminent alert range of 112 m. In both trials an imminent alert was generated immediately upon presentation of the target to the alert algorithm by the collision warning radar system at a range of 70 m. This was attributed to the radar system's capability for reporting stopped objects as valid targets at long ranges.

4.2.2 TEST 2 – HOST VEHICLE ENCOUNTERS SLOWER LEAD VEHICLE

In this verification test, the host vehicle is traveling on a straight, flat road at 50 mph and the lead vehicle is traveling ahead at 10 mph in the same lane. Five trials were performed on 15 October 2001. Based on the specified vehicle speeds and accelerations, the theoretical early, intermediate, and imminent collision alert ranges for Mid sensitivity are 82 m, 72 m, and 61 m, respectively. The alert ranges from the verification test data are shown in Table 4-1.

Table 4-1 Test 2 Slower Lead Vehicle Alert Ranges for Mid Warning Sensitivity

	Alert Range (m)		
Trial	Early Alert	Intermediate Alert	Imminent Alert
1	107	90	70
2	103	87	70
3	104	86	68
4	100	87	70
5	102	76	67

The differences between the theoretical and measured alert ranges were primarily caused by the resolution of the relative acceleration. The reported value for A_R was one quantization level below the expected value of 0. This caused the alert ranges to increase about 20 m, 12 m, and 8 m, respectively, for the early, intermediate, and imminent collision alerts. While in this case the resolution of A_R caused the alerts to be given early, in other cases it could cause the alerts to be given later.

The remainder of the alert range differences was due to small deviations from the desired speeds. Also, the intermediate alert range in the fifth trial seems inconsistent with the other four trials. This occurred because an A_R of 0 m/s^2 was reported for six time intervals preceding the change in alert level. A change to the next lower quantization level of A_R triggered the intermediate alert.

4.2.3   TEST 3 – LEAD VEHICLE BRAKES HARD

In this test the host vehicle is traveling on a straight, flat road at 60 mph and the lead vehicle is traveling ahead at 60 mph in the same lane. The host and lead vehicles are initially spaced at a moderate distance (approximately 38 m). The lead vehicle brakes hard (approximately -0.3 g), and the host vehicle approaches the braking lead vehicle. Four trials were performed on 27 September 2001. The theoretical early, intermediate, and imminent collision alert ranges for Mid sensitivity are 38 m, 37 m, and 34 m, respectively. The alert ranges from the verification test data are shown in Table 4-2. The differences between the theoretical and test ranges can be attributed to slight differences in speed, lead vehicle deceleration, and initial range.

Table 4-2 Test 3 Lead Vehicle Braking Alert Ranges for Mid Sensitivity

Trial	Alert Range (m)		
	Early Alert	Intermediate Alert	Imminent Alert
1	40	38	36
2	36	36	34
3	39	39	38
4	41	40	37

4.2.4   TEST 9 – HOST VEHICLE TAILGATES BRAKING LEAD VEHICLE

For Test 9 the host vehicle is traveling on a straight, flat road at 60 mph and the lead vehicle is traveling ahead at 60 mph in the same lane. The host vehicle is tailgating the lead vehicle at a close distance (approximately 16 m). The lead vehicle brakes (approximately -0.2 g), and the host vehicle approaches the braking lead vehicle. An accelerometer in the lead vehicle was used in this test to measure A_L. Two trials were performed on 27 September 2001 (one in Near sensitivity and one in Mid).

In this scenario the Tailgating Mode is active at the beginning of each test run. When Tailgating Mode is enabled, an imminent collision alert is expected when a relative acceleration of about –0.2 g is detected or when the Standard Mode imminent-collision conditions are reached. Tailgate Mode cautionary alerts are based on range thresholds (see Section 2.5). The true initial range for both test runs was 19 m. In both cases the lead vehicle braked at about –0.3 g. In Mid sensitivity, the early alert is On at the start of the test, as expected. For Near sensitivity, all alerts were Off at the onset of the test. The imminent collision alert was provided 0.7 s and 0.6 s after the lead vehicle commenced braking for Mid and Near sensitivities, respectively. Four-tenths of a second of this time is because of averaging in the algorithm; the remainder is the time required for the lead

vehicle to ramp to –0.3 g deceleration. The Standard Mode imminent collision alert conditions were met in this test at 2.0 s (Mid) and 1.6 s (Near) after the start of lead vehicle braking. This delay in the Standard Mode alerts, as compared to the Tailgating Mode alerts, is primarily because of filtering of A_R in the radar system. In these tests, the Tailgating Mode of the NHTSA Algorithm issued an imminent alert 1.0 s to 1.3 s earlier than the Standard Mode, providing the driver with additional time to react.

4.2.5 TEST 15 – HOST VEHICLE APPROACHES STOPPING LEAD VEHICLE

In this test the host vehicle is traveling on a straight, flat road at 40 mph and the lead vehicle is traveling ahead at 40 mph in the same lane. The host and lead vehicles are initially spaced at a large distance (approximately 107 m). The lead vehicle brakes very hard (approximately -0.5 g), and the host vehicle approaches the braking lead vehicle. Two trials were performed on 27 September 2001 with Mid sensitivity.

The theoretical early, intermediate, and imminent collision alert ranges for the two tests with Mid sensitivity are 81 m, 71 m, and 60 m, respectively. The alert ranges from the data for the first trial were 82 m, 73 m, and 63 m, respectively. The alert ranges from the data for the second trial were 72 m, 65 m, and 55 m, respectively. The differences are mainly due to variability of the actual test conditions (braking was not constant at –0.5 g).

4.2.6 TEST 20 – LEAD VEHICLE SUDDENLY MOVES AHEAD OF HOST VEHICLE

In this test the host vehicle is traveling on a straight, flat road at 50 mph and the lead vehicle traveling at 60 mph suddenly moves ahead of the host vehicle. In this situation an imminent collision alert is considered to be a nuisance. One trial was performed on 27 September 2001. The warning sensitivity was set to Mid. One-half second after the lead vehicle suddenly moved ahead, the host vehicle received an intermediate alert at 9 m. As the lead vehicle pulled farther away from the host vehicle, the alert level dropped from intermediate to early at 13 m and turned off completely at 16 m. No imminent collision alert was issued. The early and intermediate alerts were issued while the algorithm was in Tailgating Mode.

4.2.7 TEST 28 – HOST VEHICLE PASSES LEAD VEHICLE

In this test the host vehicle is traveling on a circular track at 40 mph and the lead vehicle is traveling ahead at 40 mph in the same lane. The host vehicle accelerates and passes the lead vehicle at a range of about 30 m. Two trials were performed on 27 September 2001. In this test any alert issued is considered to be a nuisance. No alerts were issued during these trials.

4.3 PUBLIC ROAD TESTING

In addition to the verification tests, the JHU/APL project engineers conducted public road testing during the algorithm development effort. This testing consisted of normal driving on a variety of road types in the Detroit, MI area to obtain qualitative impressions from driving the test vehicle and to identify algorithm shortcomings that may not have been addressed in the verification

tests. Several areas requiring attention were identified over the course of the public road testing. These included the following:

     a. Nuisance alerts from roadside objects in low speed situations

     b. Nuisance alerts while braking

     c. Nuisance alerts in "passing" situations

     d. Alerts while "tailgating"

     e. Alerts for vehicles changing into the host vehicle's lane

     f. Alerts for vehicles turning off the roadway

An important area of observation during the public road testing was whether or not the driver felt that the alerts received were an annoyance. Several categories of such nuisance alerts were identified. One of these categories involved the collision warning system radar reporting curbs, signs, trees, etc., as stationary targets at very close range. These often resulted in alerts when they occurred at low speeds in parking lots and on urban and residential streets when turning a corner. Inhibiting alerts while the host vehicle speed was below 20 mph eliminated almost all of these nuisance alerts. Although true collision warning events can occur in these low speed situations, drivers are usually attentive in low speed situations and the risk of injury to the driver or a passenger is much less.

Another area where drivers experienced unwanted alerts was when the driver felt the situation was "under control," such as when the driver was braking while approaching a stopped or slower vehicle. In response to this concern, the algorithm inhibited cautionary alerts when the brake is pressed. In addition, to reduce the occurrences of imminent collision alerts under these conditions, the driver reaction time was reduced from 1.6 to 0.5 s while the driver is braking. This reduction reflects an assumption that a driver is attentive while actively engaging the brakes.

A second source of nuisance alerts while "under the driver's control" occurs in "passing" situations. The host vehicle may be following at the same speed as the lead vehicle and then accelerate, change lanes, and pass. Alternatively, the host may approach a slower vehicle at constant but higher speed in anticipation of changing lanes to pass. The former case can be detected by monitoring host vehicle acceleration. When a positive acceleration threshold is exceeded, all alerts are inhibited. This assumes that only an alert driver would accelerate. While the current algorithm uses acceleration, a significant change in the accelerator position may be a better indicator because it more directly reflects the driver's intent. No detection scheme has been implemented for the latter case because the host driver's attentiveness cannot be inferred. Identifying a lane change maneuver via a vision system interpretation of road markings or an identifiable steering maneuver could eliminate some nuisance alerts of this type.

Another area of development initiated by public road testing was the "tailgating" mode of the algorithm. Initially, the algorithm consisted of only the "standard" mode that principally identified situations in which the host and lead vehicles differ significantly in speed or deceleration. During highway driving, it was observed that drivers could approach uncomfortably close to a lead vehicle traveling at a similar speed without receiving an alert. This situation was considered likely for an inattentive driver and a mode for "tailgating" situations was added.

A final observation involved vehicles that change lanes into the host vehicle's lane or "cut-in" at relatively close range. In the current collision warning system, "cut-in targets" are not selected for collision-warning evaluation until they have completely entered the host vehicle's lane. For a scenario in which a slower vehicle cuts in, the range to the "cut-in" vehicle might easily decrease by 10 m between the time the target vehicle first crosses the lane marker and the time it is selected as the CIPV. In scenarios of this type, radar data on the "cut-in" vehicle are normally available in the track file significantly before incursion into the host lane begins. More timely recognition of "cut-ins" could improve driver confidence in the system.

4.4 INPUT DATA QUALITY

Because the current values of measured parameters are used in the NHTSA Algorithm miss-distance calculation, the accuracy of the input data affects algorithm performance. Overall, the quality of data provided by the prototype collision warning system used for the testing reported in this section was good. Nevertheless, a few cases deserve further discussion to provide insight into the effects input data quality can have on the performance of the algorithm. These cases involved the effects of target switching, resolution, and V_H accuracy.

At ranges less than 30 m a radar system can often identify multiple reflection points on the rear surface of a target vehicle as separate targets. This situation is shown in Figure 4-1. Each reflection point is assigned a different track number and is treated by the system as a different target with similar range and range rate to the other targets. At ranges of less than 20 m, the target selection algorithm of the collision warning system often switched the CIPV among the tracks that represent the single target vehicle. The NHTSA Algorithm responds to a change in track number by clearing alerts and internal status conditions. This target switching behavior can delay or prevent a valid alert. Additional processing was added to the NHTSA Algorithm to identify track number changes of this type and to suppress the clearing of alerts and internal status conditions for these cases.

The resolution used to report input parameters can affect the performance of the algorithm causing alerts to be issued at other than the theoretical times. The resolution used for A_R was the principle source of error in the slower lead vehicle test reported in this section. This resolution can in some cases cause the time of issuance of an alert to change by up to 350 ms. A reasonable objective in setting the resolution of a parameter is to avoid errors that change the timing of an alert by one-half the time accuracy of the system (one-half of 100 ms or 50 ms). For A_R, simulation has determined that a numeric accuracy of 0.07 m/s² is sufficient to provide timing accuracy to 50 ms. Errors because of the accuracy of V_H can also affect the timing of alerts. In order to provide 50 ms timing accuracy, a V_H accuracy of 0.2 m/s is needed. Although V_H was handled with 0.1 m/s precision by the collision warning system, the speed sensor only reported a V_H reading when its value changed by 1 km/hr (0.28 m/s).

Figure 4-1 Example of Multiple Tracks Assigned to a Single Vehicle

4.5 <u>VEHICLE TESTING SUMMARY</u>

The standard mode of the algorithm performed correctly during this testing; cautionary and imminent collision warning alerts were issued at the appropriate times. It was noted that data quality and resolution and the operation of the collision warning system could affect the performance of the algorithm, resulting in alerts at other than the theoretical ranges. Table 4-3 presents representative results from this testing.

The tailgating mode of the algorithm also performed as designed with cautionary alerts issued at the expected ranges and imminent alerts issued within 0.7 s of lead vehicle braking (at approximately –0.3 g) at a range of approximately 16 m. This resulted in approximately an additional second of reaction time being provided to the driver of a 60-mph vehicle, as opposed to the operation of the standard mode of the algorithm. The algorithm did not issue nuisance alerts during tests covering the situations of accelerating to pass a lead vehicle and a faster vehicle suddenly moving in front of the host vehicle at close range.

Table 4-3 NHTSA Algorithm Test Performance

Test	Imminent Warning Range (m)		
	Theoretical	Average Result	Comments
Stopped Lead Vehicle*	112	70	Alert issued immediately upon receipt of target from the radar system.
Slower Lead Vehicle**	61	69	Early alert due to resolution of relative acceleration.
Braking Lead Vehicle†	34	36	Braking profile did not exactly match specified test conditions.
*Host Vehicle Speed: 60 mph. **Host Vehicle Speed: 50 mph, Lead Vehicle Speed: 10 mph. †Host and Lead Vehicle Speeds: 60 mph, Lead Vehicle Braking: -0.3 g, Initial Range: 38 m.			

Section 5

SYSTEM PERFORMANCE SIMULATION

5.1 <u>SIMULATION SCENARIO</u>

This section presents the results of a detailed simulation of the performance of the NHTSA Algorithm when used in a vehicle equipped with a prototype collision warning system. The objective of the simulation is to estimate the proportion of rear-end collisions that can be avoided for an example scenario with the use of the NHTSA Algorithm. The scenario analyzed is the stopped lead vehicle scenario from Section 3, a host vehicle traveling at 60 mph approaching a stopped lead vehicle. The driver of the host vehicle is assumed to be inattentive and will not initiate braking until T_R seconds of reaction time after an alert is issued. The braking model described in Appendix B was used to represent driver braking behavior (i.e., how hard the driver brakes after being warned). The initial range for the simulation is set at 250 m. Collision warning radars are typically limited to ranges of about 120 m; the simulation assumes an ideal radar that can report targets at long ranges.

5.2 <u>SIMULATION RESULTS</u>

Figure 5-1 shows the results of a single simulation run (Trial No. 1). For presentation purposes, V_H is scaled by a factor of 5 and A_H by a factor of –10. Here, the alert is issued when the host vehicle is about 104 m from the lead vehicle. In this particular trial, the driver reaction time is 1.6 s. Thus, the driver did not begin braking until the range was around 61 m. Initially, the driver brakes hard. Once the situation has resolved itself, the driver "eases up" on the brake until the host vehicle comes to a full stop 2.2 m away from the lead. A second simulation run (Trial No. 2), with a slower reaction time of 2.1 s, is shown in Figure 5-2. Here the driver begins braking too late (48 m from the lead vehicle) to avoid a collision. In this particular trial, the collision occurs with a DeltaV of 6.8 m/s. DeltaV refers to the difference in velocities between the host and lead vehicles at the moment of impact. Because the lead vehicle is stopped in this scenario, DeltaV is equivalent to the host vehicle velocity at the point of impact.

This simulation is repeated 10,000 times for each value of T_R and for different values of A_{Hmax}. The results are presented in Figures 5-3 and 5-4. Figure 5-3 illustrates the probability of collision versus driver reaction time for three values A_{Hmax} (-0.35g, -0.55 g, and –0.75 g) including the setting of the NHTSA Algorithm (-0.55 g). Figure 5-4 shows the average DeltaV, when a collision does occur, versus reaction time. The results in Figures 5-3 and 5-4 show that for the NHTSA Algorithm (A_{Hmax} = -0.55g), the driver has 1.8 s to react. Driver reaction times greater than 2.3 s are almost certain to result in a collision. Thus, there exists a half-second duration of uncertainty where a collision may or may not occur depending on the random parameters of the model.
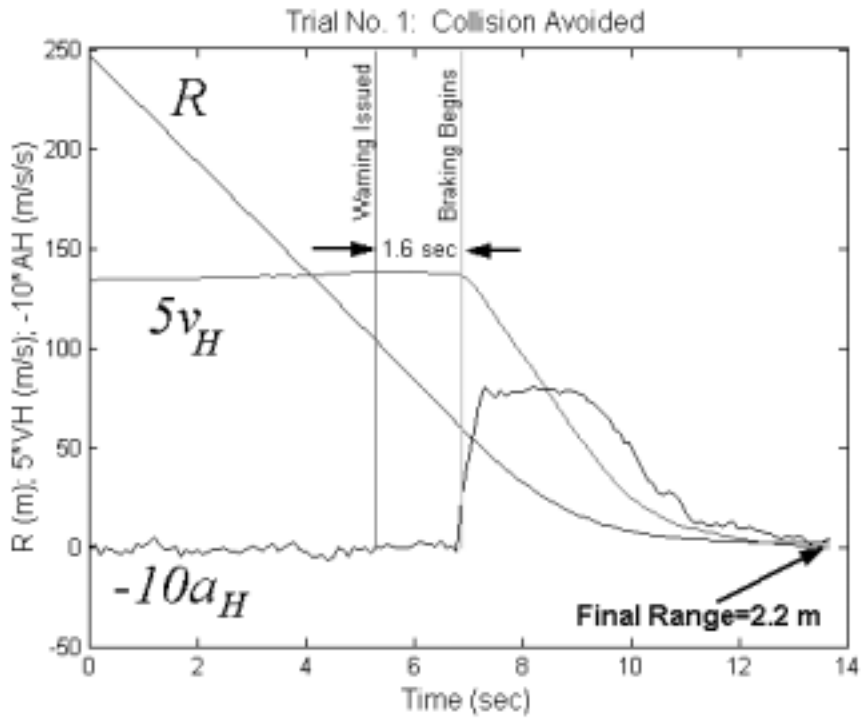
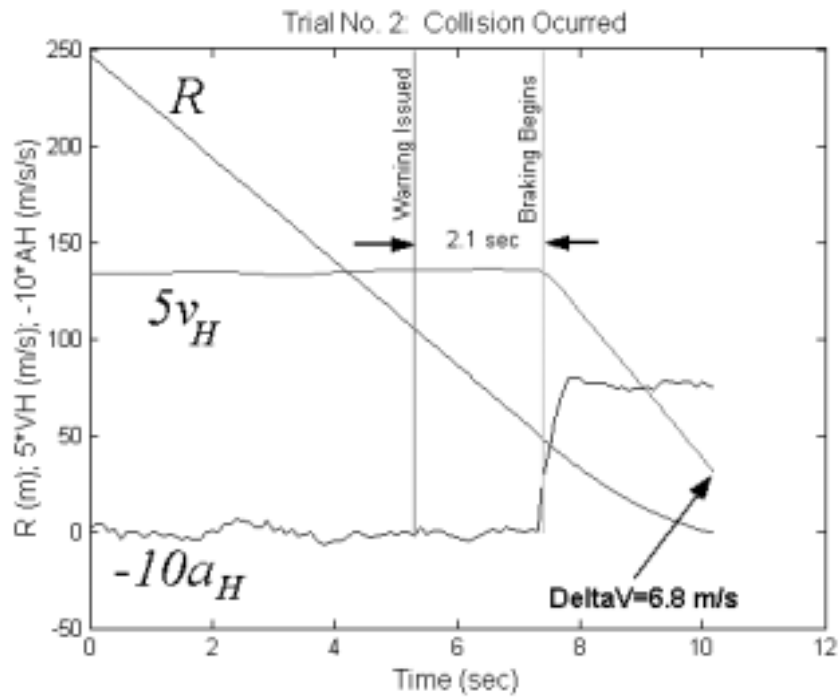**Figure 5-1 Trial No. 1 Results - Collision Avoided (T_R = 1.6 s, Near Sensitivity)**

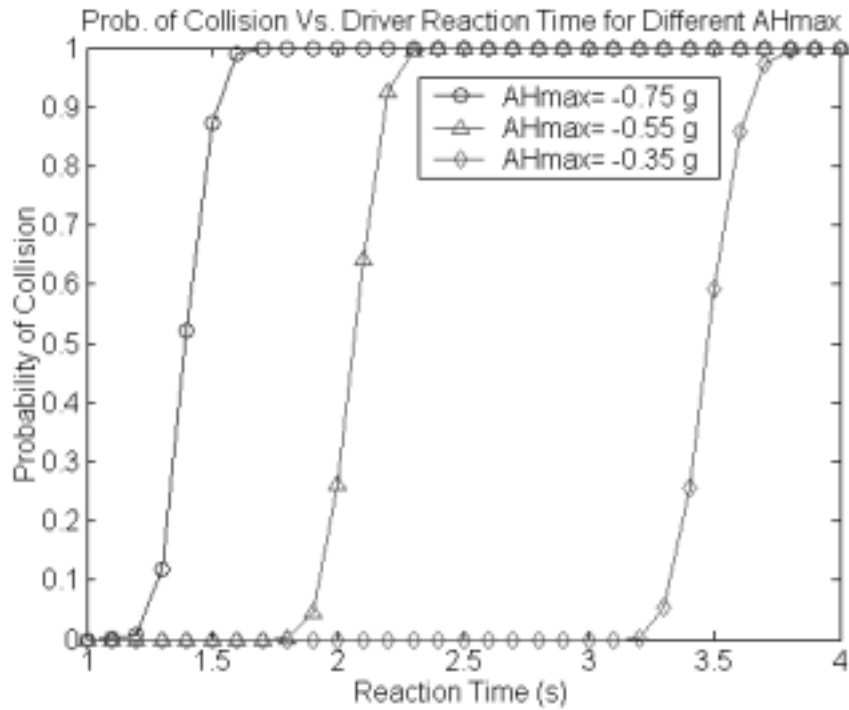**Figure 5-2 Trial No. 2 Results - Collision Occurred (T_R = 2.1 s, Near Sensitivity)**

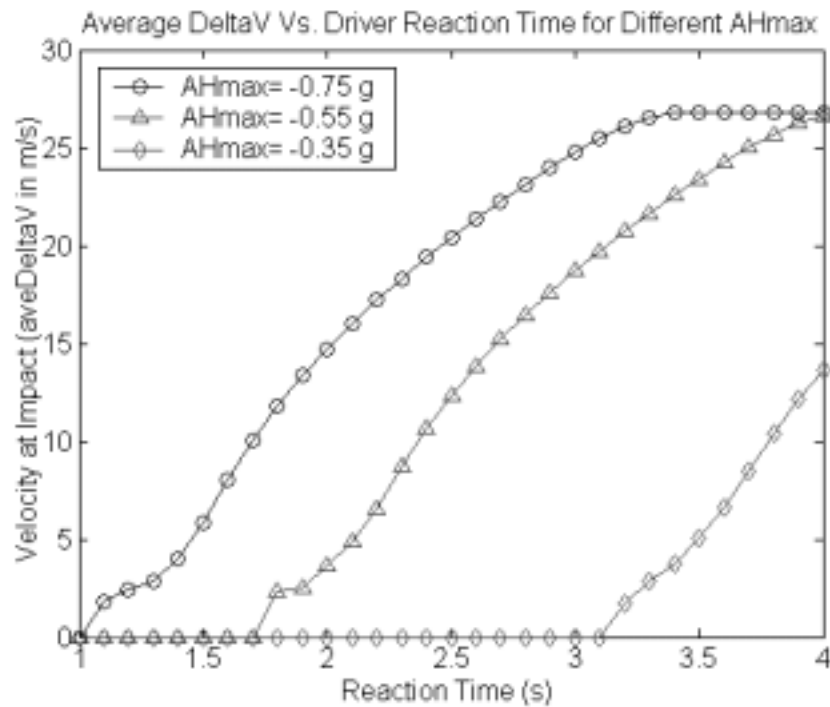**Figure 5-3 Probability of Collision Versus Reaction Time (10,000 Trials per Point)**

Figure 5-4 Average DeltaV Versus Reaction Time (10,000 Trials per Point)

Figure 5-3 shows the conditional probability of collision, conditioned on T_R. To determine the unconditional probability of collision, a probability distribution on T_R is needed. In the available previous works on driver reaction time, the lognormal distribution has been used (References 5 and 8 to 11). Let X be a Gaussian random variable with mean zero and variance one, then

$$T_R = \lambda e^{\zeta X} \tag{5-1}$$

is a lognormal random variable with median λ and dispersion parameter ζ. The mean and variance of T_R are

$$\mu = \lambda e^{\zeta^2/2}, \text{ and } \sigma^2 = \mu^2 (e^{\zeta^2} - 1). \tag{5-2}$$

Different authors have reported different values of λ and ζ. Table 5-1 shows the values of λ and ζ derived in four different studies (Reference 7).

Table 5-1 Driver Reaction Time Models Based on the Lognormal Distribution

Driver Reaction Time Model	Median λ	Dispersion Parameter ζ	Mean μ	Standard Deviation σ
Chang et al. (Reference 5)	1.10	0.53	1.30	0.74
Sivak et al. (Reference 9)	1.07	0.49	1.21	0.63
Wortman and Matthias (Reference 10)	1.14	0.44	1.30	0.60
Gazis et al. (Reference 11)	1.12	0.27	1.14	0.32

The probability distribution functions of these four models are shown in Figure 5-5. To derive the unconditional probability of collision, the rule of total probability is used:

$$\Pr(Collide) = \int_0^\infty \Pr(Collide \mid T_R = t) f_{T_R}(t) \, dt. \tag{5-3}$$
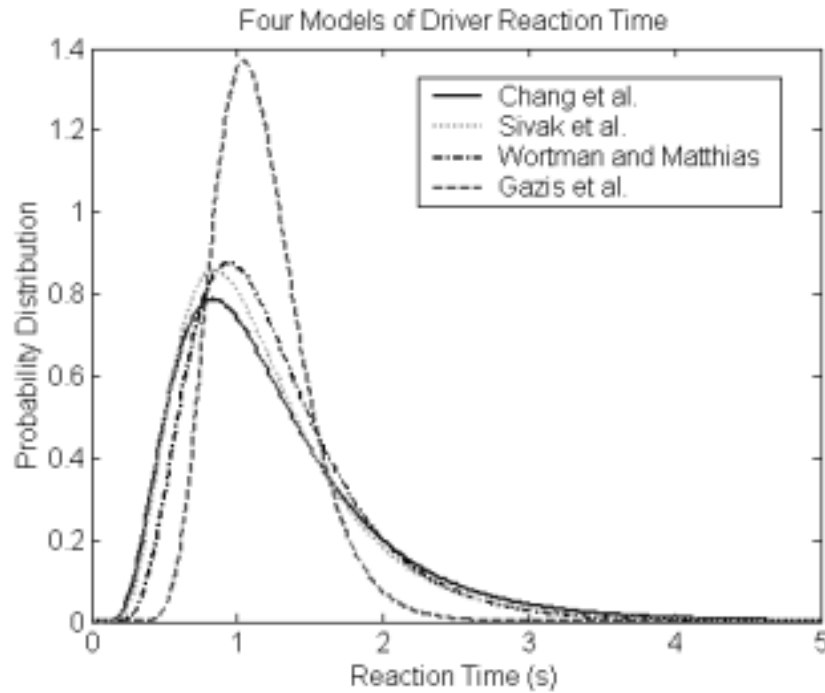
Figure 5-5 Four Driver Reaction Time Models Based on the Lognormal Distribution

The previous integral has been calculated numerically, and the unconditional probabilities of collision are presented in Table 5-2. It is assumed that reaction time is independent of sensitivity setting, speed, and range. The probabilities of collision vary widely depending on which reaction time model is selected. Chang et al. (Reference 5) is the most pessimistic model, while Gazis et al. (Reference 11) is the most optimistic. The NHTSA Algorithm, with A_{Hmax} = -0.55g, had a probability of collision ranging between 0.017 and 0.129 for a 60-mph host vehicle approaching a stopped lead vehicle.

Table 5-2 Unconditional Probability of Collision for Different Reaction Time Models and Assumed Host Vehicle Maximum Braking Capabilities

Reaction Time Model	Unconditional Probability of Collision		
	A_{Hmax}		
	-0.75 g	-0.55 g	-0.35 g
Chang et al. (Reference 5)	0.353	0.129	0.016
Sivak et al. (Reference 9)	0.321	0.100	0.009
Wortman and Matthias (Reference 10)	0.354	0.100	0.006
Gazis et al. (Reference 11)	0.254	0.017	0.000 02

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Section 6

SUMMARY

The NHTSA Algorithm issues collision alerts designed to allow a driver to stop or approach no closer than a designated distance (nominally 2 m) behind a stopped or slower vehicle in its lane of travel. In addition to its standard mode of operation, it includes provisions for tailgating and ACC modes of operation. The algorithm was subjected to analysis, tests, and simulation to determine its performance. The analysis and tests included theoretical analyses and verification tests with the alert algorithm installed in a test vehicle with a prototype collision warning system.

Two sets of theoretical analyses were performed. The first analysis determined the performance of the algorithm under the assumption of perfect input data for three operational scenarios representing the pre-crash conditions for many of the rear-end collisions that the collision warning system is meant to prevent. The second analysis indicated that the performance of the algorithm in terms of the Probability of False Alarm versus the Probability of a Miss is set by the choice of estimated driver reaction time and assumed host vehicle deceleration. Furthermore, this analysis indicated that the error in estimating the driver response (braking level and reaction time) has a greater effect on system performance than the error in measuring the vehicle dynamics, with the measurement noise having little effect on overall system performance.

Verification testing was conducted with the NHTSA Algorithm installed in the prototype ACAS FOT collision warning system. Highlights of the results of these tests include:

a. The theoretical performance of the standard mode of the algorithm was verified for test scenarios in which a stopped, slower, or braking vehicle is approached from a distance of 30 m or more. These test scenarios included a 60-mph host vehicle approaching a stopped lead vehicle, a 50-mph host vehicle approaching a 10-mph lead vehicle, a 60-mph host vehicle following 38 m behind a 60-mph lead vehicle that brakes at -0.3 g, and a 40-mph host vehicle following 107 m behind a 40-mph vehicle that brakes at -0.5 g. Cautionary and imminent collision alerts were issued at the appropriate times upon receipt of a target from the radar system.

b. The tailgating mode of the algorithm provided cautionary alerts at the expected ranges and imminent alerts were issued within 0.7 s of lead vehicle braking (at approximately -0.3 g) at a range of approximately 16 m. The tailgating mode of operation provided approximately an additional second of reaction time to the driver of a 60-mph vehicle, as opposed to the standard mode of the algorithm.

It was noted that in some scenarios the performance of the algorithm was dependent on the capability of the radar system to report valid targets on curves and at longer ranges. Algorithm performance was most affected when the host vehicle was traveling at higher speeds. An example of this was noted for the 60-mph stopped lead vehicle scenario for which a target was not

reported to the alert algorithm until after the NHTSA Algorithm's theoretical imminent alert range was passed. In addition, it was noted that data quality and resolution could affect the performance of the algorithm, resulting in alerts at other than the theoretical ranges.

A detailed simulation of the NHTSA Algorithm was performed to estimate the proportion of rear-end collisions that could be avoided for an example scenario. The simulation showed that with the algorithm there was a probability of collision between 0.017 - 0.129 for the scenario of a 60-mph host vehicle approaching a stopped lead vehicle, depending on the reaction time model used.

Appendix A

LIST OF REFERENCES

1. L. R. Bachman, G. R. Preziotti, J. F. Hartsonft, and J. R. Gersh, "October 1998 Rear-End Collision Avoidance Symposium Final Report," JHU/APL, VS-99-047, September 1999.

2. A. L. Burgett, A. Carter, R. J. Miller, W. G. Najm, and D. L. Smith, "A Collision Warning Algorithm for Rear-End Collisions," 16th International Technical Conference on Enhanced Safety of Vehicles (ESV), Paper No. 98-S2-P-31, 1-4 June 1998.

3. R. A. Glassco and D. S. Cohen, "Analysis of a Rear-End Collision Avoidance System (RECAS) Warning Algorith3m Using Field Operational Test Data," Mitretek Systems, Washington, DC, December 2000.

4. Wassim G. Najm, Christopher J. Wiacek, and August L. Burgett, "Identification of Precrash Scenarios for Estimating the Safety Benefits of Rear-End Collision Avoidance Systems," 5th World Congress on Intelligent Transportation Systems, 12-16 October 1998.

5. M. S. Chang, C. J. Messer, and A. J. Santiago, "Timing Traffic Signal Change Intervals Based on Driver Behavior," *Transportation Research Record 1027*, pp. 20-30, 1985.

6. P. Fancher, Z. Bareket, J. Sayer, G. Johnson, R. Ervin, and M. Mefford, "Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS)," *Department of Transportation HS 808 437*, May 1995.

7. J. K. Kuchar, "Collision Alerting System Evaluation Methodology for Ground Vehicles," *The International Society for Optical Engineering (SPIE) Proceedings,* Vol. 2902, pp. 272-283, November 1996.

8. G. T. Taoka, "Brake Reaction Times of Unalerted Drivers," *Institute of Transportation Engineers (ITE) Journal*, pp. 19-21, March 1989.

9. M. Sivak, P. L. Olson, and K. M. Farmer, "Radar Measured Reaction Times of Unalerted Drivers to Brake Signals," *Perceptual and Motor Skills 55*, p. 594, 1982.

10. R. H. Wortman and J. S. Matthias, "Evaluation of Driver Behavior at Signalized Intersections," *Transportation Research Record 904*, pp. 10-20, 1983.

11. D. Gazis, R. Herman, and A. Maradudin, "The Problem of the Amber Signal in Traffic Flow," *Operation Research 8*, pp. 112-132, March-April 1960.

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Appendix B

BRAKING MODEL

B.1 <u>INTRODUCTION</u>

This appendix describes the development of the braking model used by the collision warning system performance simulation of Section 5. The objective of this model is to predict at each instance in time the value of A_H (the negative of which is the deceleration rate). The development starts with a proposed physical model of how a driver brakes, and then, based on this physical model, a mathematical model is developed. The performance of the mathematical model is then compared with braking data obtained from a number of sources. In the braking model, the amount of braking depends on the current vehicle speed and the required stopping distance. Existing braking models were investigated prior to the development of this model. For example, Chang et al.[1] developed a model for the purpose of setting traffic signal change intervals, which includes these factors, that was deemed not fully suitable for the collision warning simulation.

B.2 <u>PHYSICAL MODEL</u>

The following statements describe the physical braking model:

a. Braking is initiated by the driver due to a warning of the presence of an obstacle.

b. The driver estimates his/her speed and the required stopping distance (i.e., how far he/she can safely travel before coming to a stop).

c. The driver applies the brake in such a way so that he/she will come to a stop before reaching the required stopping distance.

d. It is not possible for the driver to brake harder than the vehicle is physically capable of braking.

e. Even under the same circumstances (speed and distance), the driver does not react the same every time.

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[1] E-mail from Wassim G. Najm, Volpe National Transportation Systems Center, to Jack Ference, National Highway Traffic Safety Administration, "Thoughts on the MOE Program," 7 February 2001.

f. Hard braking cannot occur instantaneously (i.e., it is not possible to go from zero acceleration to –5.88 m/s² acceleration in less than 0.01 s).

The model does not include dependencies on road conditions (such as wetness and grade) because these appear to be of secondary importance (Chang et al.).

B.3 MATHEMATICAL MODEL

The mathematical model is derived from the physical model. V_H denotes the host vehicle speed in meters per second, and D_{RS} denotes the required stopping distance in meters. If the lead vehicle is stopped, then D_{RS} is equal to the range, R. However, if the lead vehicle is moving but decelerating, then the required stopping distance is the range plus the projected distance traveled by the lead vehicle before stopping:

$$D_{RS} = R - (V_L)^2 / 2A_L. \tag{B-1}$$

Where, as defined in Section 2, $V_L = V_H + RR$ and $A_L = A_H + A_R$.

If the host vehicle decelerates at a constant rate of $-A_0$, then the total distance traveled by the host vehicle before coming to a stop (D_H) is

$$D_H = - (V_H)^2 / 2A_0. \tag{B-2}$$

Or solving for A_0 :

$$A_0 = - (V_H)^2 / 2D_H. \tag{B-3}$$

Equation B-3 indicates that if a vehicle is traveling at a speed of V_H m/s and wishes to stop within D_H meters then it needs to decelerate at a constant rate of at least $-A_0$ m/s². Because it is desired to stop slightly before reaching the required stopping distance, D_H is set to be slightly smaller than D_{RS}:

$$D_H = 0.95D_{RS} - 0.5V_H - 1.5. \tag{B-4}$$

The constant 0.95 in the first term of Equation B-4 is meant to reduce the stopping distance by 5 percent for large values of D_{RS}. The second term is meant to provide a 0.5-s margin of error in the distance traveled calculation. The motivation is that the higher the speed the larger the error margin should be. The third term is meant to reduce the stopping distance by a constant value of 1.5 m for small values of D_{RS}. D_H is saturated at 0.001 m, i.e., if it is less than 0.001 m, it is set to 0.001 m. This is to prevent division by zero and positive values of A_0 (acceleration rather than braking).

Because the physical model limits the level of hard braking, the range of A_0 needs to be limited as well. Based on experience during this program, 0.8 g (or 7.84 m/s²) is about the hardest deceleration possible in passenger vehicles (see Sections B.5 and B.6). Thus, deceleration is saturated at –7.84 m/s² for values of A_0 below –7.84 m/s² and at –0.5 m/s² for values of A_0 greater than –0.5 m/s². The upper saturation level of –0.5 m/s² is meant to represent the lightest possible braking level. Equation B-5 then gives the host vehicle acceleration, A_1:

$$-7.84 \text{ if } A_0 < -7.84$$
$$A_1 = A_0 \text{ if } -7.84 \leq A_0 \leq -0.5. \hspace{3cm} \text{(B-5)}$$
$$-0.5 \text{ if } A_0 > -0.5$$

Because the physical model requires the driver to not react the same every time, a random value is added to A_1 to give a revised host vehicle acceleration, A_2:

$$A_2 = A_1 + N. \hspace{3cm} \text{(B-6)}$$

Where N is additive white Gaussian noise with mean zero and variance 0.25. Finally, because of the fact that the physical model does not allow hard braking to occur instantaneously, a simple finite-impulse response low-pass filter is used to modify A_2. This results in a predicted value of the host vehicle acceleration, A_{HP}, for the time interval i+1, based on the values of A_2 for the current and four previous time intervals:

$$A_{HP}(i+1) = 0.35A_2(i) + 0.2A_2(i-1) + 0.2A_2(i-2) + 0.15A_2(i-3) + 0.1A_2(i-4). \hspace{0.5cm} \text{(B-7)}$$

In summary the braking model at time interval i calculates a predicted value of the host vehicle acceleration, A_{HP}, for the time interval i+1 using the following steps:

a. Given the values of A_H, V_H, R, RR, and A_R, it calculates D_{RS} according to Equation B-1.

b. Given V_H and D_{RS}, it calculates D_H using Equation B-4, and if it is less than 0.001 m, setting it to 0.001 m.

c. Given V_H and D_H, it calculates A_0 according to Equation B-3.

d. Given A_0, it calculates A_1 using Equation B-5.

e. It then adds noise to A_1 to obtain A_2 using Equation B-6.

f. Finally, it filters A_2 to obtain A_{HP} using Equation B-7.

B.4   <u>COMPARISON WITH CHANG ET AL.</u>

Chang et al. proposed a braking model based on speed, required stopping distance, surface grade, and reaction time. Their model was derived from data collected from time-lapse cameras placed at signalized intersections. The motivation of their model was to optimize the traffic signal change intervals, (i.e., the "yellow time plus any following all-red interval") rather than for collision warning simulation. However, their work is related to the present work in that it proposed models for driver reaction time and braking level. This section compares the proposed model with that of Chang et al. Because their model does not include a random parameter or a low-pass filter, the focus is only on the A_0 parameter. The Chang et al. model is given by

$$A_0 = -4.07 - 0.00577(V_H)^2 + 0.0293D_{RS} - 0.085GRADE + 0.338D_{RS}/V_H - 0.044V_HT_R. \hspace{0.3cm} \text{(B-8)}$$

A comparison between the proposed model and the Chang et al. model is shown in Figure B-1. Here, $-A_0$ is plotted as a function of D_{RS} for various fixed values of V_H. GRADE is set to

zero percent (level surface), and T_R equals 1 s (the same values used in Figure 8 [Chang et al.]) Chang et al. did not plot A_0 for small D_{RS} and large V_H apparently because there were insufficient data to fit the model for such dangerous situations. In many instances, the driver chooses not to brake when he/she is traveling at high speed and is already close to the intersection. It can be seen from Figure B-1 that when data are available, the proposed model is in agreement with the Chang et al. model.
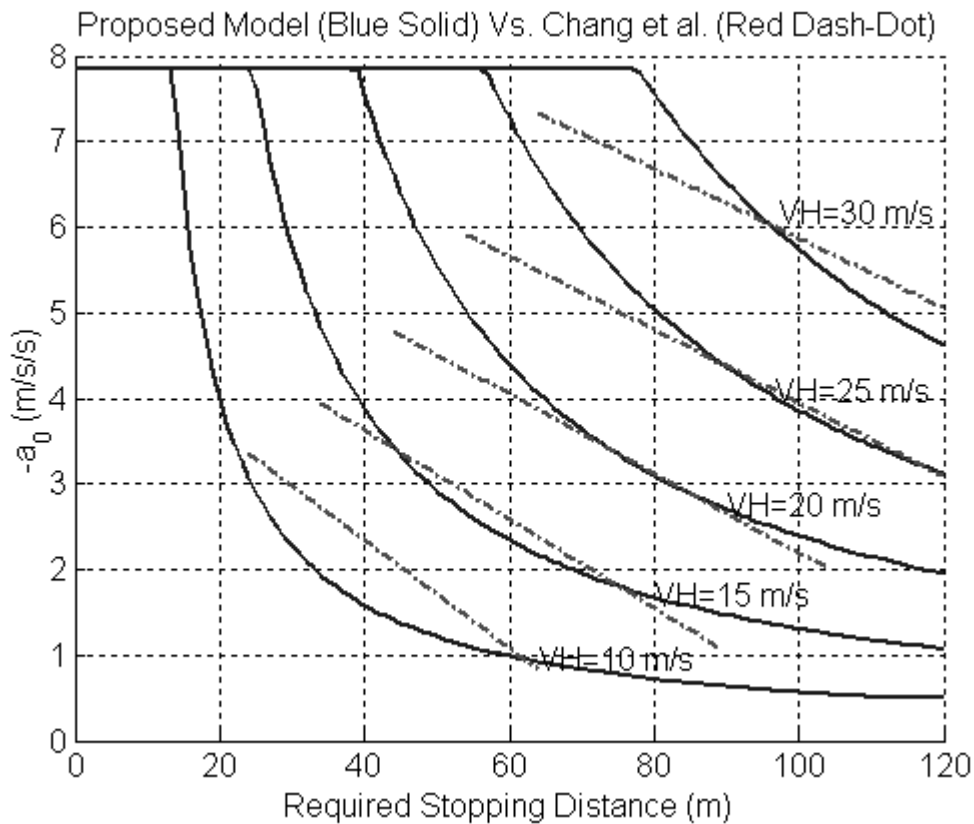

Figure B-1 Comparison of Proposed Braking Model Versus Chang et al.

B.5   COMPARISON WITH DATA COLLECTED BY THE ACAS FOT SYSTEM

Because the scenario of interest for the simulation is where the lead vehicle is stopped or stopping, it is desirable to assess the accuracy of the model under that situation. Data were recorded for such a case during testing of the prototype ACAS FOT Collision Warning System. The host vehicle was traveling at 17.5 m/s (39 mph) on a suburban street, and the lead vehicle was 30 m in front and was braking to a stop. Figure B-2 plots A_{HP} (predicted from data values in the previous five time intervals) and the actual values of A_H. In the calculation of D_{RS} in Equation B-1, A_L is derived from A_H. In order to prevent past values of A_H from being used to predict the present value, A_L is set to a constant value of -2 m/s^2 for this comparison.

Three observations can be drawn from Figure B-2. First, when hard braking is needed (from time 1536 to 1540 s), the model correctly predicted that hard braking is needed. When light braking is needed (from time 1540 s on), the model correctly predicted that light braking is needed. This suggests the accuracy of Equations B-3 and B-4. Secondly, the transition from hard braking to light braking in the model is representative of the transition in the actual data. This reflects the appropriateness of the low-pass filter described by Equation B-7. Finally, the variability in the model is representative of the variability in the actual data. This supports the choice of 0.25 for the noise variance in Equation B-6.
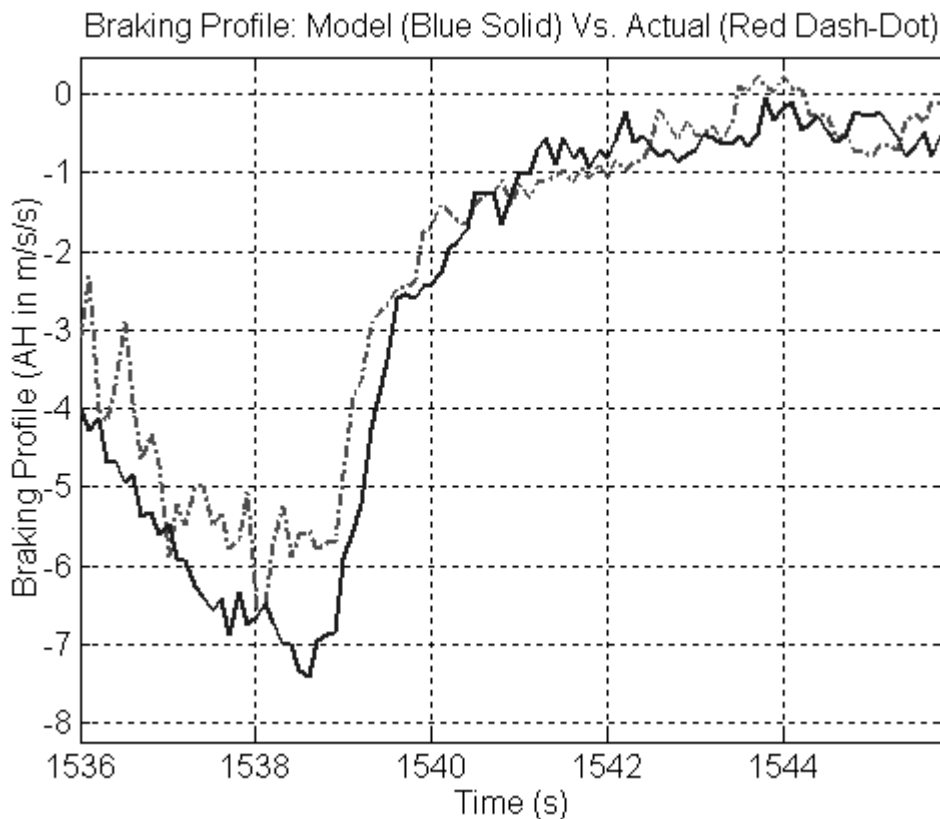

Figure B-2 Comparison of Braking Model-Predicted A_H Versus Actual Data

B.6 COMPARISON WITH JHU/APL DATA

The physical braking model states that there is a limit to the braking that can be applied, and in the mathematical model this limit is given as 0.8 g (Equation B-5). In several hours of data recorded during testing of the ACAS FOT Collision Warning System, the hardest braking experienced was in the case shown in Figure B-2 (about 0.6 g). In an attempt to confirm that 0.8 g was representative of the hardest possible braking, tests were run by JHU/APL on a vehicle (1995 Ford Ranger truck with anti-lock braking system) equipped with a commercial off-the-shelf

accelerometer to record the braking profile. The test vehicle was driven on a rural road with no traffic with an initial speed of about 50 mph. When there was no following vehicle, the brake was applied as hard as possible until the vehicle came to a full stop. This experiment was repeated four times, and in all four trials the maximum deceleration was close to 0.8 g. Figure B-3 is representative of the four trials.
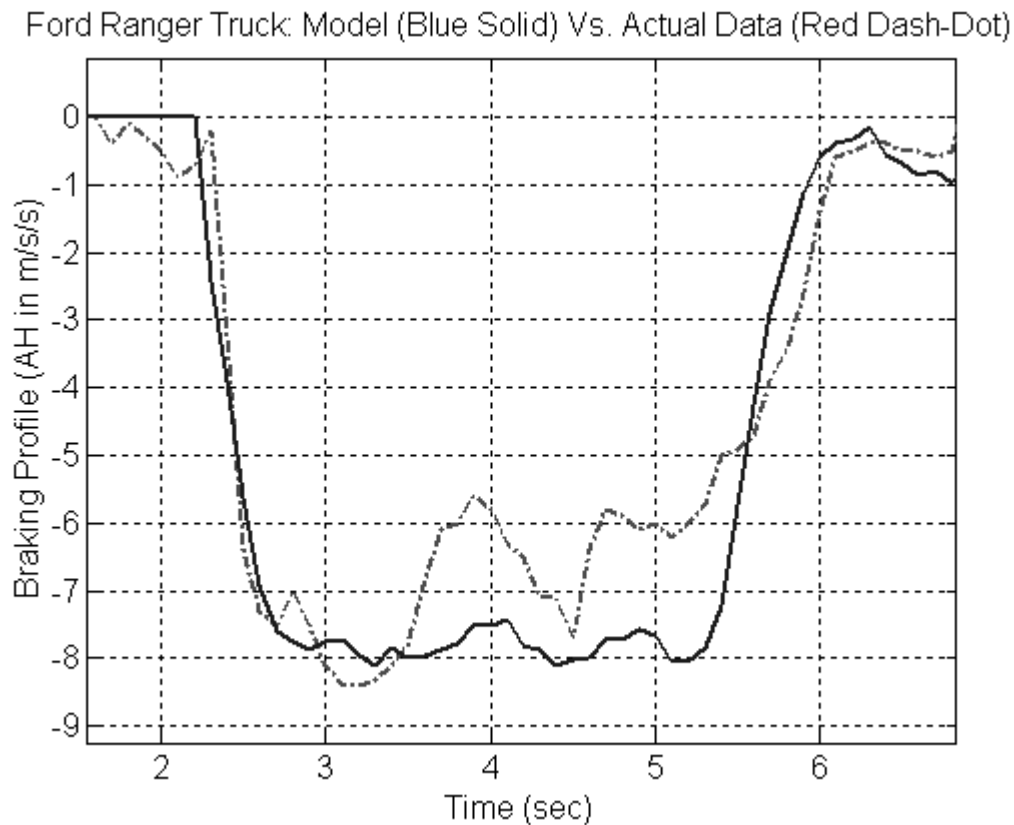

Figure B-3 Comparison of Model-Predicted A$_H$ Versus Actual Data from JHU/APL Test Vehicle

To determine how well the model fit this particular set of data, the presence of an imaginary lead vehicle stopped 2 m from where the JHU/APL vehicle came to a full stop was assumed. V$_H$ was obtained by integrating A$_H$ with boundary values V$_H$(0) = 22.35 m/s (50 mph) and V$_H$(t$_s$) =0 m/s. R was obtained by integrating V$_H$ with a final value R(t$_s$) = 2 m. It was assumed that the driver initiated braking at time 2.3 s. The model-predicted values, shown in blue (solid line) in Figure B-3, fit well with the actual data shown in red (dash-dot line).

B.7 <u>COMPARISON WITH ACN DATA</u>

It was interesting to see how well the proposed model predicts driver-braking behavior in an actual accident. Such data were available from the Automotive Collision Notification

(ACN) FOT program.[2] When an ACN-equipped vehicle was involved in a collision, the ACN system "notified emergency response personnel of the collision and the vehicle location, provided information concerning the crash, and established a voice link between the vehicle and emergency response personnel." Also, relevant to the current work, the ACN system recorded the vehicle acceleration for 2 s prior to the crash and for 8 s after the crash. One crash in the ACN FOT program was of particular interest. A verbatim description of the crash (case no. 1302) is provided:

> "The ACN-equipped 1994 Chevrolet Cavalier was southbound in the outboard (right) lane driven by a 51-year-old female. The driver was restrained at the time of the crash by the vehicle's 3-point lap and shoulder belt system. She was the sole occupant in the vehicle and was in the process of returning home after work. Stopped ahead of the Chevrolet was a 1997 Dodge full size van and a 1987 Mercury sedan. The Mercury was intending to turn right into the cemetery driveway and was waiting for traffic to clear the driveway before proceeding.

> "The crash occurred when the ACN driver failed to recognize the stopped traffic and braked too late to avoid the impact. The front plane of the Chevrolet struck the back plane of the Dodge van in a 12 o'clock/6 o'clock impact configuration. Analysis of the crash damage indicated the Chevrolet under rode the vans rear bumper. The force of the crash then displaced the van forward into a secondary front-to-rear collision with the Mercury. The vehicles came to rest in the outboard southbound lane, in-line with each other. The Chevrolet Cavalier sustained disabling damage and was towed. The Dodge van and Mercury sedan drove away from the scene. The ACN driver was tired and indicated she may have closed her eyes momentarily prior to the impact."

The ACN driver sustained multiple injuries and was transported to the emergency room of a local hospital. The acceleration data from this crash is shown in Figure B-4. Note the compressed time axis: The collision occurs within 0.3 s upon initialization of braking. The data show that, even in this imminent-collision scenario, it was difficult to brake much harder than 0.8 g. It is estimated that the initial speed was around 42 mph and the speed at impact was around 26 mph. The deceleration rate was more than 16 g at impact. The model-predicted values are derived, as in the previous subsection, except as follows: Because the sampling rate in the ACN system is 180 Hz (rather than 10 Hz), the noise variance and the low-pass filter are different than those described previously. This particular collision is indicative of one that might have been avoided (or at least, its severity could have been reduced) had the vehicle been equipped with a properly designed collision warning system.

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[2]L. R. Bachman and G. R. Preziotti, "Automated Collision Notification (ACN) Field Operational Test (FOT) Evaluation Report," JHU/APL, VS-01-008, February 2001.
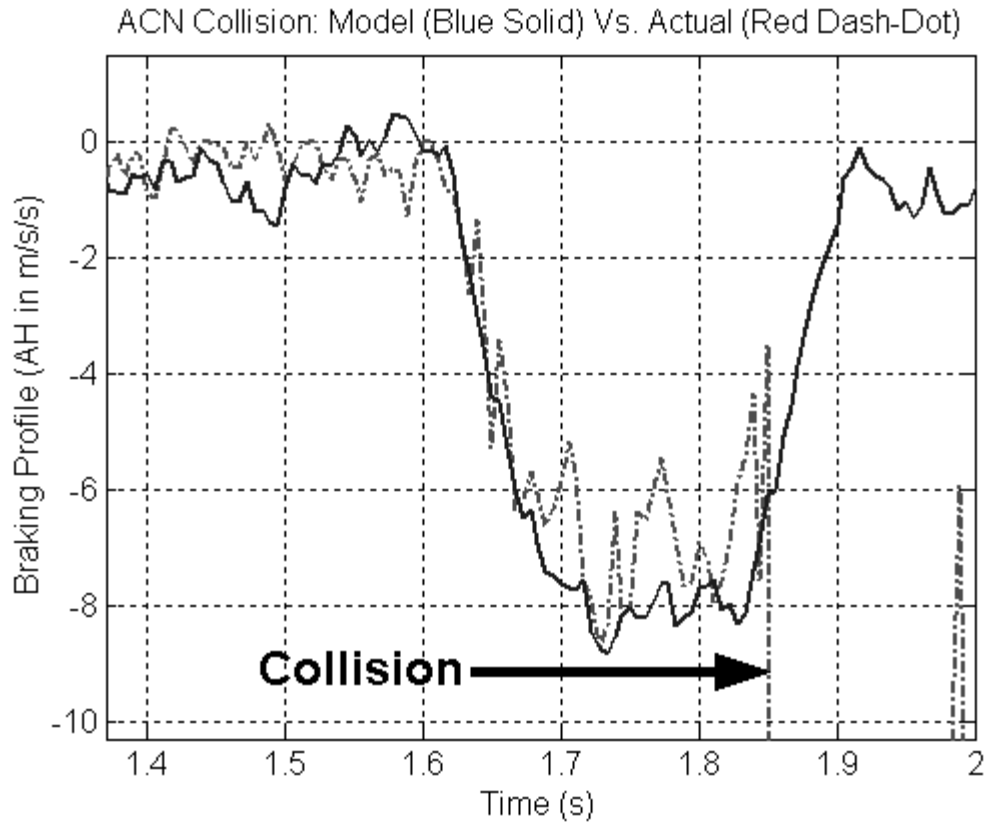
Figure B-4 Comparison of Model-Predicted A_H Versus Actual Data from ACN Collision

Appendix C

LIST OF ACRONYMS AND ABBREVIATIONS

ACAS   Automotive Collision Avoidance System

ACC   Adaptive Cruise Control

ACN   Automotive Collision Notification

A_H Host Vehicle Acceleration

A_{Hmax} Assumed Host Vehicle Maximum Braking Capability

A_L Lead Vehicle Acceleration

A_R Relative Acceleration

CIPS   Closest In-Path Stationary Object

CIPV   Closest In-Path Moving Vehicle

D_{miss} Miss Distance

D_{thresh} Miss-Distance Threshold

EDV   Engineering Development Vehicle

FOT   Field Operational Test

GES   General Estimates System

GM   General Motors

ITS   Intelligent Transportation Systems

JHU/APL   The Johns Hopkins University Applied Physics Laboratory

NHTSA   National Highway Traffic Safety Administration

PFA   Probability of False Alarm

PIHP   Moving Vehicle Projected to Enter Host Vehicle's Path

P_{miss} Probability of a Miss

R   Range

RR   Range Rate

T_{HS} **Time for Host Vehicle to Stop**

T_{LS} **Time for Lead Vehicle to Stop**

T_M **Time for Miss Distance**

T_R **Reaction Time**

V_H **Host Vehicle Velocity**

V_L **Lead Vehicle Velocity**

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