Integrated Vehicle-Based Safety System

Objective Test Scenario Warning Strategies: Kinematic Analyses and DVI Outputs

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16. Abstract

The Integrated Vehicle-Based Safety Systems (IVBSS) program is a four-year, two phase cooperative research program conducted by an industry team led by the University of Michigan Transportation Research Institute (UMTRI). The program goal is to integrate several collision warning systems into one vehicle in a way that alerts drivers to potential collision threats with an effective driver vehicle interface (DVI), while minimizing the number of excessive warnings presented to the driver. Basic program strategies for meeting this objective include systematically managing and prioritizing all information presented to the driver, minimizing the number of system false alarms, and restricting auditory alarms to higher urgency collision conditions.

This report presents a series of analyses conducted by the DVI team on a subset of relevant driving scenarios to identify: the applicable warning algorithms, the corresponding DVI output, any potential ambiguities or conflicts in defining these detection algorithms and DVI outputs, and any potential issues in the time available to the driver to respond to the IVBSS warning.

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Jack Ference is the contracting officer's technical representative at NHTSA. Wassim Najm and Sandor Szabo lead efforts at the Volpe National Transportation Systems Center and the National Institutes for Standards and Technology, respectively, to support NHTSA.

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List of Acronyms and Abbreviations

DVI	Driver-Vehicle Interface
FCW	Forward Collision Warning
IVBSS	Integrated Vehicle-based Safety Systems
HT	Heavy Truck
LCM	Lane Change Merge
LDW	Lane Departure Warning
LED	Light Emitting Diode
NHTSA	National Highway Traffic Safety Administration
POV	Principal Other Vehicle
RT	Perception-Reaction Time
SV	Subject Vehicle
TTC	Time-to-Collision
UMTRI	University of Michigan Transportation Research Institute

Executive Summary

Overview

This document is intended to support the Integrated Vehicle-based Safety Systems (IVBSS) Heavy Truck (HT) development team by compiling information relevant to system warning strategies and Driver-Vehicle Interface (DVI) outputs. As the IVBSS development team has identified objective test scenarios, the DVI team has analyzed a subset of these scenarios to identify the applicable warning algorithms, the corresponding DVI output, any potential ambiguities or conflicts in defining these detection algorithms and DVI outputs, and any potential issues in the time available to the driver to respond to the warning.

Specifically, kinematic analyses have been performed for the forward collision scenarios RE-1 through RE-7 in an effort to determine whether the DVI approach is reasonable and robust for mitigating the potential collision conditions associated with each Forward Collision Warning (FCW) objective test scenario. In addition, the analyses were performed to determine whether the current time-headway threshold algorithm results in warnings that provide adequate driver response time or whether a Time-To-Collision (TTC) algorithm would be more suitable (or necessary) for reducing the potential for or severity of collisions.

Methodology

The kinematics analyses were performed both analytically and graphically. The analytical model was used to calculate elapsed time, vehicle speeds and positions, time headway, range, TTC, and onset of warning levels at specific times or events in the scenario. The analysis in each scenario determined whether collisions occurred and the relative speed of impact under various conditions of driver perception-reaction time (RT) and braking deceleration.

The graphical method was used to corroborate the analytical results and to achieve a visual sense of the dynamic behavior of the vehicles and warning levels under the various test conditions. Subject vehicle (SV) and principal other vehicle (POV) positions and FCW warning levels were plotted on a graph using the initial conditions of range (distance between vehicles), initial speeds, and decelerations as specified in each operational test scenario. SV deceleration occurred in response to the FCW-5 warning, after system latency, driver RT, and braking initiation delays were applied. The graphical results were compared with those in the analytical approach to ensure that the outcomes were consistent. An example of the output from a graphical FCW analysis is illustrated in Figure E-1 below.

In both the analytical and graphical analyses, the system latency and braking initiation delay were held constant, while driver RT and SV deceleration rates were varied to test for collisions under varying combinations of these two variables. Three levels of driver RT were evaluated: 0.75 seconds (alerted driver); 1.5 seconds (non-alerted driver); and 2.5 seconds (distracted driver). The vehicle kinematics were evaluated for all scenarios using moderate SV deceleration (-0.25 g). Additional analyses were performed using stronger braking decelerations (-0.4g and -0.5 g) for scenarios in which collisions occurred under the modest -0.25g braking condition.

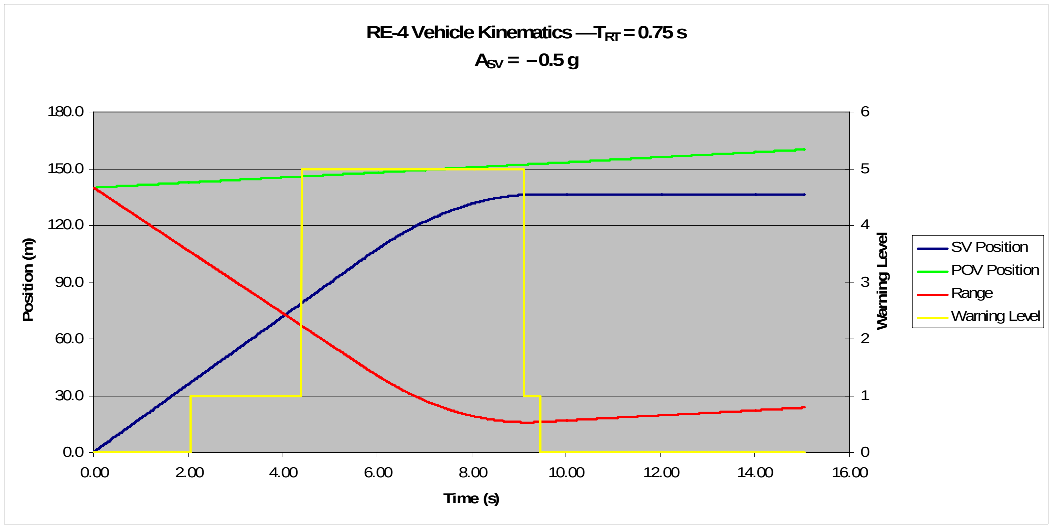


Figure E-1. Example of the output from the graphical kinematics analysis.

Findings

Scenarios RE-1, -5, -6, and -7 represent situations in which there is a relatively small difference in speed between the SV and POV, and in which both vehicles are traveling at constant speed, until the SV decelerates in response to the FCW-5 warning. In each of these scenarios, it is possible to avoid a collision, even when the RTs are consistent with distracted driving (i.e., RT ≤ 2.5 seconds). In contrast, when there is a large difference in speed (such as in Scenario RE-4) or when the POV is decelerating (such as in Scenarios RE-2 and -3), the requirements for collision avoidance are more stringent. Aggressive braking (-0.4g or stronger) is required to avoid collisions in conditions where RT is 1.5 seconds or less, and even harder, -0.5g braking is insufficient to avoid a collision with an RT of 2.5 seconds, the longest RT tested for these scenarios.

The current time headway approach for determining warning level appears to generate warnings that provide sufficient RT, and generally results in consistent and predictable TTCs, under mild to moderately severe collision conditions. However, the time headway approach is less effective in situations in which the lead POV is decelerating, or in which there exists a large difference in speed between the vehicles. Depending on the outcome of the IVBSS jury drives and the pilot testing planned for the Summer and Fall of 2006, it may be worthwhile to explore the use of a TTC algorithm, or to consider modifying the time headway values in the current algorithm, for scenarios resulting in more severe conditions of deceleration or differential speed.

It should be noted that these results are related to the specific conditions in the IVBSS FCW objective test scenarios and may not necessarily be generalizable to all situations. Particularly, these results may not apply to complex situations such as multi-threat scenarios and those in which the POV cuts in and decelerates.

Differences between These Analyses and Later Methodologies

The analyses reported herein reflect the methodology and state of the DVI in early January, 2007 when these analyses were performed. Two additional FCW warning levels have been added subsequent to these analyses to account for special conditions in developing rules for integration of FCW, Lane Change Merge (LCM), and Lane Departure Warnings (LDW). Also, a different methodology has been adopted for subsequent analyses, which determines available RT for collision avoidance (or severity reduction) rather than assuming RT and determining whether collisions occur. This report does not attempt to update the results to reflect the more recent methods.

1 Introduction

This is a working document that is intended to support the Integrated Vehicle-based Safety Systems (IVBSS) Heavy Truck (HT) development team by compiling information relevant to system warning strategies and Driver-Vehicle Interface (DVI) outputs. As the IVBSS development team has identified objective test scenarios, the DVI team has analyzed a subset of these scenarios to identify the applicable warning algorithms, the corresponding DVI output, any potential ambiguities or conflicts in defining these detection algorithms and DVI outputs, and any potential issues in the time available to the driver to respond to the warning.

The team has relied upon project source documents in conducting these analyses. Currently available documents that we are using in these analyses are listed below.

- IVBSS HT System Verification Plan **Draft**, University of Michigan Transportation Research Institute (UMTRI), Rev. 1.0, January 8, 2007

- IVBSS HT Performance Specifications Report **Draft**, UMTRI November 29, 2006

- Discretionary Cooperative Agreement for IVBSS, National Highway Transportation Safety Administration (NHTSA)

- Mike Lesher's Forward Collision Warning (FCW) Level Descriptions (see Appendix A)

- Eaton VORAD VS-400 system description presentation materials

- **Draft** IVBSS Heavy Truck DVI Design Document/Guideline, Version 2.0, November 7, 2006.

- *Scenario Classification* spreadsheet prepared by the project team (note that the nomenclature for scenario identification in the *Scenario Classification* document is used—and expanded upon—in the present document)

In addition to supporting the IVBSS HT Verification Plan, the present effort is intended to support the revision of the IVBSS HT DVI Design Document/Guideline (listed above). Specifically, the review and clarification of issues associated with these objective test scenarios is intended to provide a basis for the further consideration of alternative detection algorithms; as well as additional scenarios that may support definition of the full range of potential detection algorithms and DVI outputs.

The main body of this document is intended to be divided into the five categories of test procedures specified in the IVBSS HT System Verification Plan, as summarized below. *Note that only Category 1 scenarios were analyzed for the current version of this document.*

1. Forward Collision Warning (Rear End) – *this is the only section that has been completed in the January 18, 2007 version*

2. Road Departure Warning

3. Lane Change Merge Warning

4. Multiple Threat Warning

5. No Warning

2 Forward Collision Warning (Rear End) Required Objective Test Procedures

This section describes FCW headway warning conditions, DVI outputs, and vehicle kinematics calculations that were conducted as part of the review of the required FCW objective test scenarios and provides a review of each FCW required objective test scenario.

Kinematic analyses were performed for forward collision scenarios RE-1 through RE-7 in an effort to determine whether the DVI approach is reasonable and robust for mitigating the potential collision conditions associated with each FCW objective test scenario. In addition, the analyses were performed to determine whether the current time-headway threshold algorithm results in warnings that provide adequate driver response time or whether a Time-To-Collision (TTC) algorithm would be more suitable (or necessary) to reduce the potential for or severity of collisions.

This section describes the analyses and is organized into the following subsections:

- FCW Headway Warning Conditions and DVI Outputs
- Kinematics Analysis Methodology
- Review of FCW Required Objective Test Scenarios
- General Findings
- Differences between These Analyses and Later Methodologies

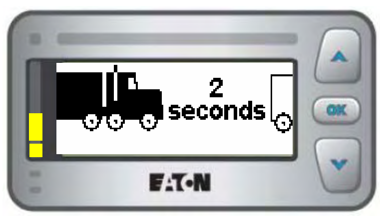
Following these sections, three appendices are presented that support the definitions, methods, and results of these analyses. Appendix A comprises the algorithms used to determine the current warning level based on time headway, relative vehicle speeds, and range. Appendix B provides a series of graphs depicting the range between the two vehicles from the onset in the scenario as well as the time when each applicable DVI output algorithm criterion is met. These graphs represent the kinematics for the three perception-reaction times in response to the FCW-5 warning. The vehicle kinematics were evaluated for all scenarios using moderate SV deceleration (-0.25 g). Additional analyses were performed using stronger braking decelerations (-0.4g and -0.5 g) for scenarios in which collisions occurred under the modest -0.25g braking condition. Appendix C documents the equations and algorithms used in predicting vehicle kinematics in the seven FCW object test scenarios.

2.1 FCW Headway Warning Conditions and DVI Outputs

The following headway warning levels, identified in the November 7, 2006 version of the DRAFT IVBSS HT DVI Design Document/Guidelines are assumed to be applicable to all FCW test procedures[1]. Detection algorithms are defined in Appendix A.

[1] Since the time that these analyses were performed, it became expedient to refine the imminent warning algorithm by partitioning the FCW-5 into two additional imminent warning conditions. Consequently, the stationary object condition was allocated to FCW-6, and the slow-moving object condition was allocated to FCW-7. These additional levels were added to facilitate the development of rules for integrating the LCM and/or LDW subsystem messages with those from the FCW subsystem.

Table 1. Headway warning levels tested in these analyses.

DVI Output	Detection Algorithm	Visual Display	Auditory Display
FCW-1	Forward object detected R < 106 m and Thw > 3 s		None
FCW-2	Forward object < 3 sec headway and closing 3 s > Thw > 2 s	 (small yellow LED-steady illumination)	None
FCW-3	Forward object < 2 sec and closing 2 s > Thw > 1 s	 (two LED segments-steady illumination)	Short alert: 1800 Hz; 80 ms 600 Hz; 80 ms
FCW-4	Forward object < 1 sec and closing 1 s > Thw > 0.5 s	 (3 LED segments-steady illumination)	Double alert: 1800 Hz; 80 ms 600 Hz; 80 ms 1800 Hz; 80 ms 600 Hz; 80 ms
FCW-5	Forward object < 0.5 seconds (opening or closing), Thw < = 0.5 s OR Stationary Object Algorithm OR Slow Moving Object Algorithm	 (Red LEDs – steady illumination)	Repeating alert: 1800 Hz; 80 ms 600 Hz; 80 ms 1800 Hz; 80 ms 600 Hz; 80 ms Pause 180 ms; Repeat…

2.2 Kinematic Analysis Methodology

The kinematics analyses were performed using Microsoft Excel. Elapsed time, vehicle speeds and positions, time headway, range, TTC, and onset of warning levels were calculated at specific events, such as at warning level transition ranges, at the beginning of subject vehicle (SV) and/or principal other vehicle (POV) deceleration, at SV and/or POV stopping, and at collision points, etc. These parameters were calculated analytically using the equations (or derivations thereof) listed in Appendix C of this document. The analysis in each scenario determined whether collisions occur under various conditions of driver perception-reaction time (RT) and braking deceleration; in the event of a collision, the relative speed at impact was also determined.

A graphical method was also used to corroborate the analytical results, with SV and POV positions calculated at 10 millisecond intervals. Parameters that affected instantaneous SV position included SV speed, overall braking delays, and SV deceleration rate. Braking delays included SV target acquisition and processing time (system delay), driver RT and time between application of pressure on the brake pedal and onset of deceleration (vehicle braking latency). Instantaneous POV position was determined by initial speed, distance from the SV, and deceleration rate. The position data, range (relative distance between vehicles), and warning level were plotted on a graph at each time interval. The graphical results were compared with the analytical results to ensure consistency of results and also to achieve a visual sense of the behavior of the vehicles under the various test conditions. An example of the output from a graphical FCW analysis is illustrated in Figure 1.

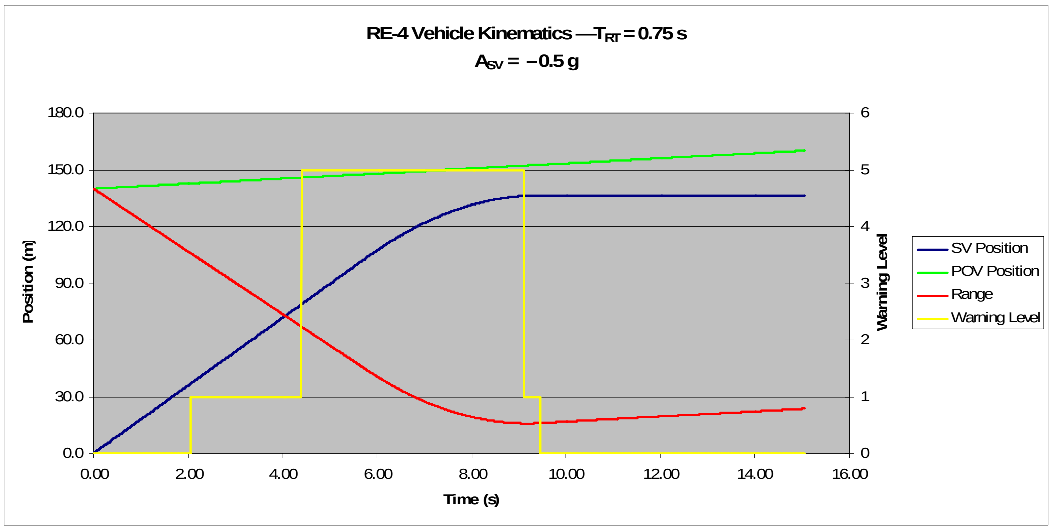


Figure 1. Example of the output from the graphical kinematics analysis

In both the analytical and graphical analyses, the system delay and braking latency were held constant, while driver RT and SV deceleration rate were varied to test for collisions under varying combinations of these variables. Three levels of driver RT were evaluated: 0.75 seconds (alerted driver); 1.5 seconds (non-alerted driver); and 2.5 seconds (distracted driver). All FCW scenarios were evaluated using SV deceleration of -0.25 g (-2.45 m/s^2). Braking at this level of deceleration resulted in collisions under conditions in which there were large differences in initial vehicle speeds or in which the POV was decelerating. To determine whether these collisions could be avoided by applying harder braking, a series of post hoc analyses were performed using -0.4g (-3.92 m/s^2) and -0.5 g (-4.90 m/s^2) deceleration rates for scenarios RE-2, -3, and -4. These deceleration values were used because it was determined that the moderate braking of -0.25 g represented average braking over a range of representative hazard situations, while the more aggressive -0.4 g and -0.5 g decelerations represented rare (but not unknown) emergency braking conditions.

The following algorithm provides a detailed description of how the graphical analyses were performed:

1. SV behavior was calculated and plotted on the graph:

    a. The time of onset of FCW-5 was taken from the analytical model[2].

    b. SV deceleration initiation time was calculated by adding the overall delay (i.e., system latency, driver RT, and braking initiation delay) to the FCW-5 onset time.

    c. The SV deceleration value for the given test was applied in the position equation for cells in which the elapsed time was greater than or equal to the SV deceleration initiation time.

    d. The change in SV position during a given interval was calculated based on the position, speed, and acceleration at the end of the previous interval.

    e. SV speed was held at zero if the SV decelerated to a stop or because of a collision.

2. The POV behavior was plotted on the graph in a similar manner:

    a. The onset of POV deceleration (if any) was applied in the position equation for cells in which the elapsed time was greater than or equal to timings as specified in the scenario description.

    b. The change in POV position was calculated at each interval based on the position, speed, and acceleration during the previous interval.

    c. POV speed was held at zero if the SV decelerated to a stop or because of a collision.

[2] Because the graphical model depended in part on some of the results from the analytical model, an informal validation of the graphical analysis was performed using a later graphical model that was developed for determining available perception-reaction time in later analyses. This later model depends only on the dynamic values of parameters as they occur and requires no a priori analytical calculation of timings. Although comparisons between the original and newer graphical methodologies were not made for all scenarios and combinations of variables, the results were consistent for the sampling of scenarios that were evaluated.

3. The range (i.e., distance between the front bumper of the SV and rear bumper of the POV) was calculated as the difference between the vehicle positions and was plotted on the graph.

4. The warning level at each time interval was determined based on range, vehicle velocities, and time headway. The warning level also was plotted on the graph to help visualize the timing of deceleration relative to warning onset.

An intersection of the SV and POV positions indicated a collision; both SV and POV positions remained equal and constant for the duration of the scenario after a collision occurred. The range, positions, and collision points were examined to verify that they were consistent with the analytical results.

2.3 Review of FCW Required Objective Test Scenarios

The following test scenario reviews are based on vehicle kinematics calculations for the scenarios described in the December 1, 2006 objective test descriptions. (Note that some scenario information included in the December 1, 2006 draft document was removed from the January 8, 2007 version of that document. Consequently, the scenario reviews are based on the earlier version of the document because the later version did not provide sufficient information to generate the kinematics calculations).

Each review consists of a description of the scenario and tables that provide the outcomes of the analyses. This section describes the format and heading definitions used in the reviews of the FCW test scenarios and data tables.

Each scenario description includes the following information:

General Description: Defines the purpose for the test scenario and the general test conditions.

Test Scenario References: References that justify the test parameters.

IVBSS Interactions: Describes potential interactions between warning subsystems (i.e., LDW and LCM).

General Detection Algorithms: Identifies the algorithm used to trigger FCW-5.

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: Identifies possible system integration conflicts between LCM, LDW, and/or FCW detection algorithms or DVI messages.

Possible Driver Response Issues: Lists potential issues that may be specific to driver response and general results based on the kinematics analyses.

Each scenario review includes a table with the headings that are defined below.

Vehicle: Subject Vehicle (SV) or Primary Other Vehicle (POV).

V (m/s): Initial velocity at the start of the scenario.

Acc (m/s^2): Acceleration. Note that negative values of acceleration indicate vehicle deceleration. Onset of acceleration is assumed to occur at the start of the scenario unless otherwise noted.

T (s): Elapsed time of the scenario, with T=0 indicating the beginning of the scenario as described in *IVBSS Heavy Truck System Verification Plan Draft*, UMTRI, Rev. 1.0, December 1, 2006. Subsequent Times indicate the calculated time when the physical relationship between the two vehicles defined by a given Detection Algorithm is met.

R (m): Range between SV and POV at the time when the physical relationship between the two vehicles defined by a given Detection Algorithm is met.

Applicable Detection Algorithm: The IVBSS Detection Algorithm that applies to the current time in the scenario.

T_{hw}: Headway Time – One of the variables used in the IVBSS Forward Collision Warning System criteria for determining the transition to FCW-5. In the tables, T_{hw} is the time headway at the instant the FCW-5 is presented.

Time of Collision: These values are calculated from T = 0 in the scenario. Note that the ∞ symbol indicates that no collision occurred. Separate times of collision are provided for each of three delay periods, using the following parameters:

- **System delay** of 140 ms from onset of scenario conditions that meet the applicable Detection Algorithm condition. This delay is constant for all test conditions in all scenarios.

- **Driver RT** of 0.75 sec (alerted), 1.5 sec (non-alerted), and 2.5 sec (distracted)

- **Vehicle braking system initiation time** of 0.5 sec. This delay is constant for all test conditions in all scenarios.

  In the following FCW analyses, the combinations of System Delay, Driver RT, and Braking Initiation Time result in three different Total Delay Periods identified as conditions "a", "b", and "c" as summarized in Table 2 below.

Table 2. Summary of Total Delay Periods in seconds.

	Total Delay Periods (sec)		
	a	**b**	**c**
System Delay	0.14	0.14	0.14
Driver RT	0.75	1.50	2.50
Braking Initiation Time	0.50	0.50	0.50
Total Delay	**1.39**	**2.14**	**3.14**

SV Braking Deceleration: All scenarios were evaluated using SV braking deceleration of -0.25 g (-2.45 m/s^2). Scenarios that resulted in collisions under -0.25g braking conditions were also evaluated using SV braking deceleration of -0.4 g (-3.92 m/s^2) and -0.5 g (-4.90 m/s^2). In these scenarios, a second table is provided indicating the time of collision and the relative speed of impact for each combination of SV braking deceleration and subject RT[3]. Additional heading definitions specific to these second tables are as follows:

V_{SV}: Subject vehicle velocity at the time of collision

V_{POV}: Primary other vehicle velocity at the time of collision

$V_{collision}$: Difference in speeds at the time of collision; specifically $V_{collision} = V_{SV} - V_{POV}$

The following sections provide the results of the analysis for each IVBSS FCW objective test scenario.

[3] Although the table lists only the subject RT, the other two delay elements, system latency and brake initiation delay, were included in the kinematic calculations.

2.3.1 RE-1 Rear-end conflict with a constant speed POV

This test is intended to verify the appropriateness of an FCW when the SV approaches, from behind, a slower moving POV in the center of the same lane. In this test the SV and POV are traveling at a constant speed with a speed differential between the SV and POV of at least 8.9 m/s (20 mph).

Test Scenario References:

- IVBSS HT FCW2 – Shared-lane scenarios, “FCW2A1”: SV approaching slower POV moving at constant speed
- CAMP-RE-2
- Volpe baseline crash-imminent scenario: BCS-D2

IVBSS Interactions: None

General Detection Algorithms: This involves the “Approaching Slower Vehicle” algorithm of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: None

- FCW-5 criteria are met at T = 3.93 when R = 67 m and all Driver RTs result in adequate braking to avoid a collision. Minimum ranges between SV and POV, assuming no driver braking prior to the FCW-5 warning, are:

  Driver RT = 0.75 s, R_{min} = 25.8 m

  Driver RT = 1.50 s, R_{min} = 17.4 m

  Driver RT = 2.50 s, R_{min} = 6.2 m

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 3. RE-1 scenario conditions and results.

Vehicle	V (m/s)	Acc (m/s^2)	T (s)	R (m)	Applicable Detection Algorithm	T_{hw}	Time of Collision		
							a (.75)	b (1.5)	c (2.5)
SV	24.6	0.0	3.93	67.0	V_{pov} / V_{sv}<= 0.80 AND R <= 67 m	2.72	∞	∞	∞
POV	13.4	0.0							

2.3.2 RE-2 Rear-end conflict with slowing POV and a short time gap

This test is intended to verify the appropriateness of an FCW when the SV approaches, from behind, a modestly slowing POV.

Test Scenario References:

- IVBSS HT FCW2 – Shared-lane scenarios, "FCW2B1": SV approaching decelerating POV with a short time gap (Note that we adjusted the earlier scenario to begin with R = 120 m.)
- CAMP-RE-3
- Volpe baseline crash-imminent scenario: BCS-D3

IVBSS Interactions: None

General Detection Algorithms: This involves the "Approaching Slower Vehicle" algorithm of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: Assuming no driver actions had been taken prior to the onset of FCW-5; which immediately follows a FCW-1 warning:

- The FCW-5 warning results in a collision at all Driver RT values

Estimated Scenario Event Timing for Braking in Response to FCW 5

Table 4. RE-2 scenario conditions.

Vehicle	V (m/s)	Acc (m/s^2)	T (s) @ FCW-5	R (m) @ FCW-5	Applicable Detection Algorithm	T_{hw} (s) @ FCW-5	SV Deceleration Levels (g)		
SV	20.1	0.0	8.41	67.0	$V_{pov} / V_{sv} <= 0.80$ AND R <= 67 m	3.33	-0.25	-0.4	-0.5
POV	20.1	-1.5							

Table 5. RE-2 speed differentials at time of collision.

	Speed at Time of Collision (m/s)								
SV Deceleration (g)	-0.25 g			-0.4 g			-0.5 g		
Subject RT (s)	a (.75)	b (1.5)	c (2.5)	a (.75)	b (1.5)	c (2.5)	a (.75)	b (1.5)	c (2.5)
Time of Collision	13.5	13.0	12.7	∞	13.6	12.8	∞	∞	12.9
V_{SV}	11.00	13.97	17.17	0.00	8.33	15.3	0.00	0.00	13.59
V_{POV}	0.00	0.53	0.99	0.00	0.00	0.88	0.00	0.00	0.79
$V_{collision}$	**11.00**	**13.44**	**16.18**	∞	**8.33**	**14.25**	∞	∞	**12.80**

2.3.3 RE-3 Rear-end conflict with an aggressively slowing POV and a long time gap

This test is intended to verify the appropriateness of an FCW when the SV approaches, from behind, an aggressively slowing POV. The test is strictly longitudinal with both the SV and the POV in the center of the designated lane on a straight segment of roadway.

Test Scenario References:

- IVBSS HT FCW2 – Shared-lane scenarios, "FCW2B1": SV approaching decelerating POV with a long time gap
- CAMP-RE-3
- Volpe baseline crash-imminent scenario: BCS-D3

IVBSS Interactions: None

General Detection Algorithms: This involves the "Approaching Slower Vehicle" algorithm of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: Assuming no driver actions had been taken prior to the onset of FCW-5; which immediately follows a FCW-1 warning:

- The FCW-5 warning results in a collision at all Driver RT values

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 6. RE-3 scenario conditions.

Vehicle	V (m/s)	Acc (m/s^2)	T (s) @ FCW-5	R (m) @ FCW-5	Applicable Detection Algorithm	T_{hw} (s) @ FCW-5	SV Deceleration Levels (g)		
SV	20.1	0.0	3.83	67.0	$V_{pov} / V_{sv} <= 0.80$ AND R <= 67 m	3.33	-0.25	-0.4	-0.5
POV	10.9	-3.25							

Table 7. RE-3 speed differentials at time of collision.

	Speed at Time of Collision (m/s)								
SV Deceleration (g)	**-0.25 g**			**-0.4 g**			**-0.5 g**		
Subject RT (s)	**a (.75)**	**b (1.5)**	**c (2.5)**	**a (.75)**	**b (1.5)**	**c (2.5)**	**a (.75)**	**b (1.5)**	**c (2.5)**
Time of Collision	8.9	8.45	8.16	∞	8.92	8.23	∞	∞	8.28
V_{SV}	11.09	14.03	17.18	0.00	8.51	15.17	0.00	0.00	13.66
V_{POV}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$V_{collision}$	**11.09**	**14.03**	**17.18**	∞	**8.51**	**15.17**	∞	∞	**13.66**

2.3.4 RE-4 Rear-end conflict with slowing (nearly stopped) POV and a long time gap

This test is intended to verify the appropriateness of an FCW when the SV approaches, from behind and at a moderate speed, a stopped POV from long range in the same lane on a straight segment of roadway with both the SV and POV in the center of the designated lane.

Note: This was identified as "Rear-end conflict with stopped POV" but the December 1, 2006 test document has the POV moving at 3 mph. (*Note that the more recent version uses a fully stopped POV, which can be used in future analyses.*)

Test Scenario References:

- IVBSS HT FCW2 – Shared-lane scenarios"FCW2A2": SV approaching slower POV moving at constant speed

IVBSS Interactions: None

General Detection Algorithms This involves the "Approaching Slower Vehicle" algorithm of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: Assuming no driver actions had been taken prior to the onset of FCW-5; which immediately follows a FCW-1 warning:

- The FCW-5 warning results in a collision at all Driver RT values

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 8. RE-4 scenario conditions.

Vehicle	V (m/s)	Acc (m/s^2)	T (s) @ FCW-5	R (m) @ FCW-5	Applicable Detection Algorithm	T_{hw} (s) @ FCW-5	SV Deceleration Levels (g)		
SV	17.9	0.0	4.40	67.0	V_{pov} / V_{sv}<= 0.80 AND R <= 67 m	3.74	-0.25	-0.4	-0.5
POV	1.34	0.0							

Table 9. RE-4 speed differentials at time of collision.

	Speed at Time of Collision (m/s)								
SV Deceleration (g)	-0.25 g			-0.4 g			-0.5 g		
Subject RT (s)	a (.75)	b (1.5)	c (2.5)	a (.75)	b (1.5)	c (2.5)	a (.75)	b (1.5)	c (2.5)
Time of Collision	9.4	8.8	8.5	∞	9.5	8.6	∞	∞	8.6
V_{SV}	11.09	14.03	17.18	0.00	6.52	13.85	0.00	0.00	12.62
V_{POV}	0.00	0.00	0.00	0.00	1.34	1.34	0.00	0.00	1.34
$V_{collision}$	**11.09**	**14.03**	**17.18**	∞	**5.18**	**12.51**	∞	∞	**11.28**

2.3.5 RE-5 Test Procedure: Rear-end conflict with a slower POV after a lane change

This test is intended to verify the timeliness detecting a new in-path vehicle and the appropriateness of an FCW when the SV changes lanes to approach, from behind, a moderately slower moving POV. The lane change by the SV should occur simultaneously with the newly acquired POV entering the forward-conflict region of the FCW system.

Test Scenario References:

- FCW16 – SV changes lanes and approaches POV, FCW16A: SV cuts behind slower vehicle

IVBSS Interactions: This scenario could obtain input from the LCM system to identify the point at which the lane change has occurred to initiate the FCW DVI output.

General Detection Algorithms: This involves the "Approaching Slower Vehicle" algorithms of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: None

- FCW-5 criteria are met at T = 7.4 when R = 33 m immediately following SV lane change and all Driver RTs result in adequate braking to avoid a collision. Minimum ranges between SV and POV, assuming no driver braking prior to the FCW-5 warning, are:

  Driver RT = 0.75 s, R_{min} = 14.5 m

  Driver RT = 1.50 s, R_{min} = 9.6 m

  Driver RT = 2.50 s, R_{min} = 2.8 m

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 10. RE-5 scenario conditions and results.

Vehicle	V (m/s)	Acc (m/s^2)	T (s)	R (m)	Applicable Detection Algorithm	T_{hw}	Time of Collision a (.75)	Time of Collision b (1.5)	Time of Collision c (2.5)
SV	17.9	0.0	7.46	33.0	V_{pov} / V_{sv}<= 0.80 AND R <= 67 m	1.84	∞	∞	∞
POV	11.2	0.0							

2.3.6 RE-6 Rear-end conflict with POV after a cut-in by the POV

This test is intended to verify the timeliness detecting a new in-path vehicle and the appropriateness of an FCW when a slower moving POV changes lanes in front of the SV. The lane-change/cut-in by the POV should occur within the forward-conflict region of the FCW system on the SV.

Test Scenario References:

- FCW14 – POV cuts in front of SV, FCW14A: Slower POV cuts in front (1 or 2 lane cut-in)

IVBSS Interactions: None

General Detection Algorithms: This involves the "Approaching Slower Vehicle" algorithms of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: None

- FCW-5 conditions are met at T = 7.4 when R = 33 m immediately following SV lane change and all Driver RTs result in adequate braking to avoid a collision. Minimum ranges between SV and POV, assuming no driver braking prior to the FCW-5 warning, are:

  Driver RT = 0.75 s, R_{min} = 14.5 m

  Driver RT = 1.50 s, R_{min} = 9.5 m

  Driver RT = 2.50 s, R_{min} = 2.8 m

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 11. RE-6 scenario conditions and results.

Vehicle	V (m/s)	Acc (m/s^2)	T (s)	R (m)	Applicable Detection Algorithm	T_{hw}	Time of Collision a (.75)	Time of Collision b (1.5)	Time of Collision c (2.5)
SV	17.9	0.0	7.46	33.0	V_{pov} / V_{sv}<= 0.80 AND R <= 67 m	1.84	∞	∞	∞
POV	11.2	0.0							

2.3.7 RE-7 Rear-end conflict with a constant speed POV (motorcycle)

This test is intended to verify the appropriateness of an FCW when the SV approaches, from behind and from long range, a slower moving motorcycle in the center of the same lane.

Test Scenario References:

- FCW12 Diverse vehicle sizes (note that the current scenario description is for a passenger vehicle SV following a motorcycle and a heavy truck)

> **Note:** This is a replication of Test Procedure 1.1 with a motorcycle replacing a passenger vehicle

IVBSS Interactions: None

General Detection Algorithms: This involves the "Approaching Slower Vehicle" algorithm of the FCW system (see Appendix A)

Possible Ambiguities or Conflicts between Detection Algorithms and DVI Output: None

Possible Driver Response Issues: None

- FCW-5 criteria are met at T = 3.93 when R = 67 m and all Driver RTs result in adequate braking to avoid a collision. Minimum ranges between SV and POV, assuming no driver braking prior to the FCW-5 warning, are:

  Driver RT = 0.75 s, R_{min} = 25.8 m

  Driver RT = 1.50 s, R_{min} = 17.4 m

  Driver RT = 2.50 s, R_{min} = 6.2 m

Estimated Scenario Event Timing for Braking in Response to FCW-5

Table 12. RE-7 scenario conditions and results.

Vehicle	V (m/s)	Acc (m/s^2)	T (s)	R (m)	Applicable Detection Algorithm	T_{hw}	Time of Collision a (.75)	Time of Collision b (1.5)	Time of Collision c (2.5)
SV	24.6	0.0	3.93	67.0	V_{pov} / V_{sv}<= 0.80 AND R <= 67 m	2.72	∞	∞	∞
POV	13.4	0.0							

2.4 General Findings

None of the scenarios in RE-1 through RE-7 represent situations that would result in graded warnings beyond FCW-2; in all but scenario RE-2, the POV speed is less than 80% of the SV speed, resulting in an FCW-5 when the range decreases to 67 meters. In RE-2 and -3, the decelerating POV causes an FCW-5 to supersede graded warnings.

Scenarios RE-1, -5, -6, and -7 represent situations in which there is a relatively small difference in speed between the SV and POV and in which both vehicles are traveling at constant speed, until the SV decelerates in response to the FCW-5 warning. In all of these scenarios, it is possible to avoid a collision, even when using RTs for a distracted SV driver (i.e., RT ≤ 2.5 seconds). In contrast, when there is a large difference in speed (such as in Scenario RE-4) or when the POV is decelerating (such as in Scenarios RE-3 and -4), the requirements for collision avoidance are more stringent. In these scenarios, aggressive braking (-0.4g or stronger) is required to avoid collisions when RT is 1.5 seconds or longer; however, even hard, -0.5g braking is insufficient to avoid a collision with the longest RT tested (2.5 seconds).

The current time headway approach for determining warning level appears to generate warnings that provide sufficient RT, and generally results in consistent and predictable TTCs, under mild to moderately severe collision conditions. However, the time headway approach is less effective in situations in which the lead POV is decelerating, or in which there exists a large difference in speed between the vehicles. For example, the time-headway algorithm in Scenario RE-4 resulted in a collision speed of more than 17 m/s under the conditions tested. Depending on the outcome of the IVBSS jury drives and the pilot testing planned for the Summer and Fall of 2006, it may be worthwhile to explore the use of a TTC algorithm, or to consider modifying the time headway values in the current algorithm, for scenarios resulting in more severe conditions of deceleration or differential speed.

It should be noted that these results are related to the specific conditions in the IVBSS FCW objective test scenarios and may not necessarily be generalizable to all situations. Particularly, these results may not apply to complex situations such as multi-threat scenarios and those in which the POV cuts in and decelerates.

2.5 Differences between These Analyses and Later Methodologies

As noted earlier, two additional FCW warning levels have been added to the DVI since these analyses were performed. In these analyses, FCW-5 represented any imminent collision condition. However, the development of rules for the arbitration of LCM, LDW, and FCW messages led to the requirement that the FCW-5 stationary object and slow-moving object conditions be allocated to separate warning levels. Therefore, the FCW-6 warning level was assigned to the stationary object criteria, and the FCW-7 level was assigned to the slow-moving object criteria, leaving the 0.5 second headway criterion as the trigger for an FCW-5. All of the scenarios in the RE-1 through RE-7 operational test scenarios that resulted in FCW-5 in these analyses would result in FCW-7 using the present methodology and warning definitions. However, the FCW-5 results reported herein are left unchanged to reflect the methodology and results as they existed when the analyses were originally performed.

Another key difference exists between these analyses and the more recent methodology. In these analyses, the results (i.e., whether a collision occurred and, if so, the speed of impact) depended on the assumption of specific, predefined driver RTs. The current methodology employs an opposite approach, which determines the amount of time available to the driver to react in order to avoid a collision based on initial conditions, such as initial velocities, acceleration rates and timing, initial range, and warning level for which the driver reacts by braking. Nonetheless, the results reported herein reflect the results of the original methodology.

The purpose for developing the later methodology is to provide a generalized methodology that allows greater flexibility in changing parameters and reduces the need to develop functions for handling special situations. Also, determining the available RT provides a broader picture of the necessary driver capabilities and the related kinematic requirements in order to avoid collisions or reduce their severity. The results of subsequent analyses based on the newer approach were used to develop and validate rules for integrating FCW, LCM, and LDW warnings and DVI messages; those results are reported elsewhere.

Appendix A:
Forward Collision Warning Level Descriptions

From: MichaelKLesher@Eaton.com [mailto:MichaelKLesher@Eaton.com]
Sent: Friday, December 01, 2006 5:59 AM
To: jdev@umich.edu; jsully@umich.edu; JohnAKovacich@eaton.com; MichaelNowak@eaton.com; Campbell, John L; Dean.Pomerleau@cognex.com; Matt.Troup@Cognex.com
Subject: Description of the VS-400 warnings

Warning Level Descriptions (From Mike Lesher)

- Warnings are received only for a vehicle in the SV lane.
- Warnings are disabled in sharp turns and **when the brake is applied.**

As you approach a slower vehicle ahead:

- At 350 ft. (106 m) to the vehicle, the "Object Detected" text message is activated.
- At 3 seconds to the vehicle, one yellow indicator illuminates, the "3 Second" text message is activated.
- At 2 seconds to the vehicle, two yellow indicators illuminate, the "2 Second" text message is activated and a single beep will sound.
- At 1 second to the vehicle, three yellow indicators illuminate, the "1 Second" text message is activated, accompanied by a double beep.
- At 0.5 seconds to the vehicle ahead, all red indicators illuminate, the "Collision Alert" text message is activated and the continuous warning tone is active.

If a faster moving vehicle pulls into your lane and accelerates away:

- If less than 0.5 seconds away, all red indicators illuminate, the "Collision Alert" text message is activated with continuous warning tone.
- At 0.5 to 1 second away, three yellow indicators illuminate, the "1 Second" text message is activated and no tones.
- At more than 1 second away, two yellow indicators illuminate, the "2 Second" text message is activated and no tones.
- At more than 2 seconds away, one yellow indicator illuminates, the "3 Second" text message is activated and no tones.
- At more than 3 seconds away, the "Object Detected" text message is activated.
- At 350 ft. (106 m), no light or text messages are active.

Stationary Object
If a stopped vehicle is within 220 feet (67 m) and less than 3 seconds away, all red indicators illuminate, a continuous warning tone sounds and the "Collision Alert" text message is activated. (*Note: should this be the repeating auditory alert?*)

Slow Moving Object
If a vehicle ahead is moving 20% slower than your vehicle and is within 220 feet (67m), all red indicators illuminate, a continuous warning tone sounds and the "Collision Alert" text message is activated. (*Note: should this be the repeating auditory alert?*)

Appendix B: Predicted SV and POV Ranges in Required Forward Collision Warning Objective Test Scenarios

Graphical representations of the relationship between SV and POV in each of the required FCW objective test scenarios were prepared to help in considering the evolution of the test scenario under different driver response assumptions. The series of graphs depicts the predicted vehicle positions for each scenario, assuming driver braking at a specified warning – in the present scenarios, FCW-5 is the initial FCW that includes an auditory warning and is used as the warning that is responded to with braking on the part of the SV driver. In each graph, the position of SV and POV, as well as the SV-POV Range, is graphed from Time T = 0, which is the start of the scenario.

The time at which each applicable FCW warning level criterion is met is also depicted in these graphs. It should be noted that warning outputs would be disabled if the SV driver were braking. However, the disabling of any warnings is not depicted in the following graphs.

All scenarios were analyzed using a moderate rate of SV deceleration (-0.25 g braking) upon activation of FCW-5 warnings. Scenarios 2, 3, and 4 resulted in collisions, so additional graphical analyses were performed for these scenarios using more aggressive deceleration rates of -0.4 g and -0.5 g for each of the three driver RTs tested: 0.75 seconds (alerted driver), 1.5 seconds (unalerted driver), and 2.5 seconds (distracted driver).

RE-1: Rear-end conflict with a constant speed POV

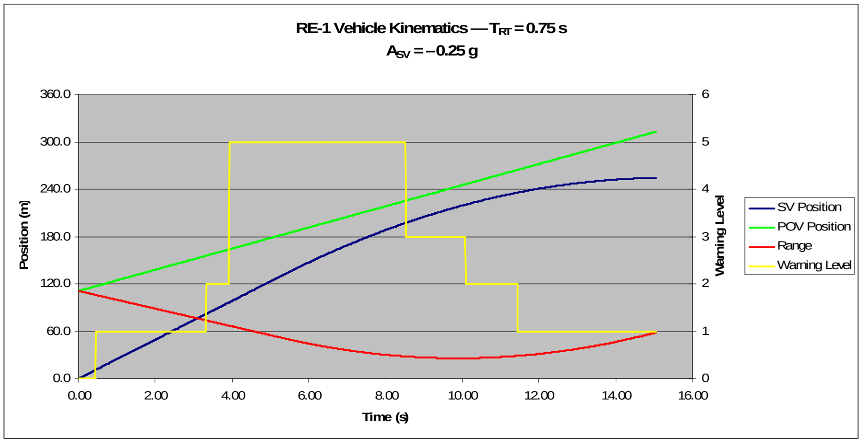


Figure B-1. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-1: Rear-end conflict with a constant speed.

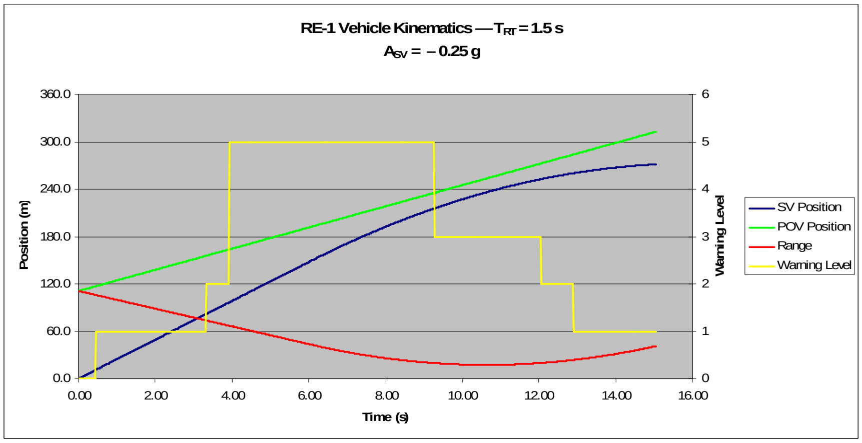


Figure B-2. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-1: Rear-end conflict with a constant speed.

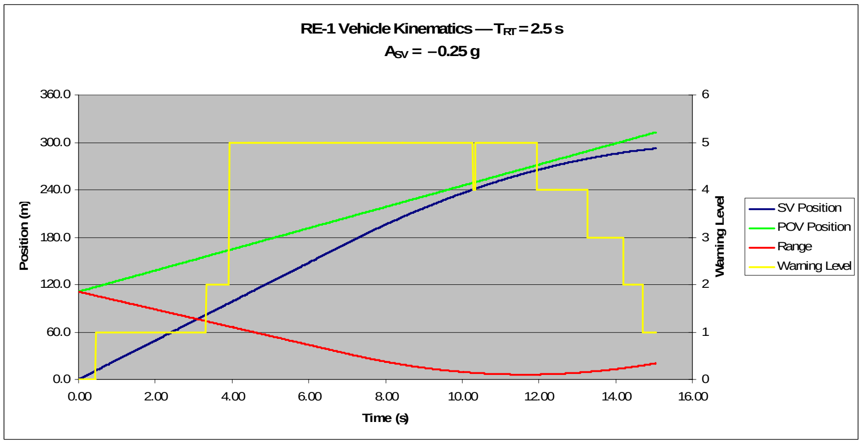


Figure B-3. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-1: Rear-end conflict with a constant speed.

RE-2: Rear-end conflict with slowing POV and a short time gap

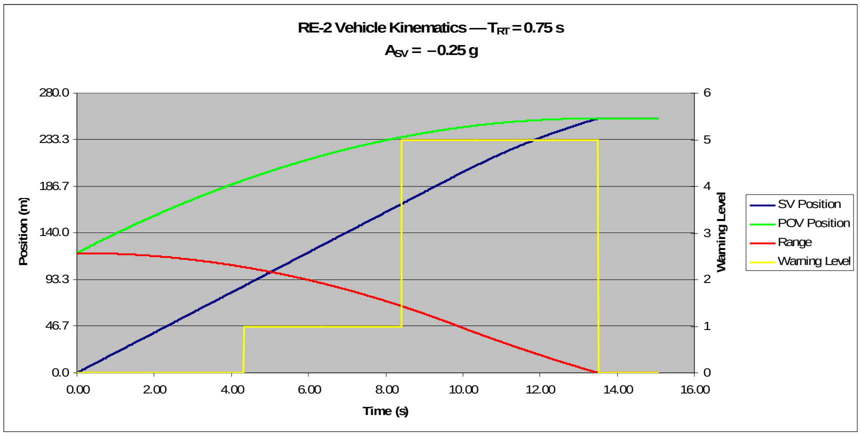


Figure B-4. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

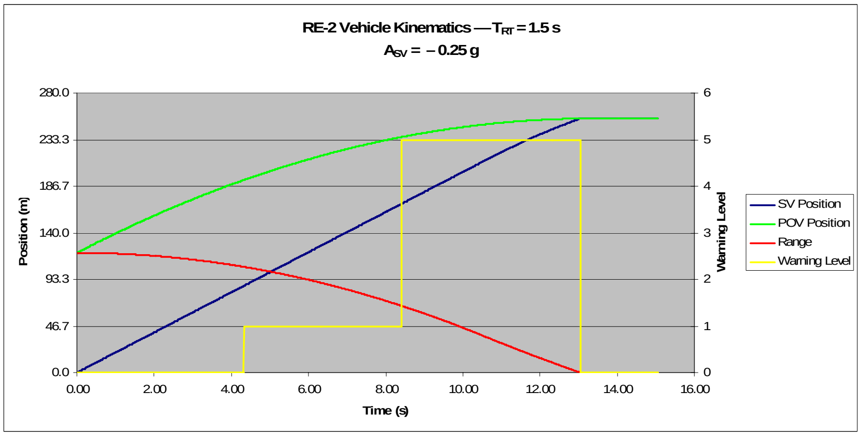


Figure B-5. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

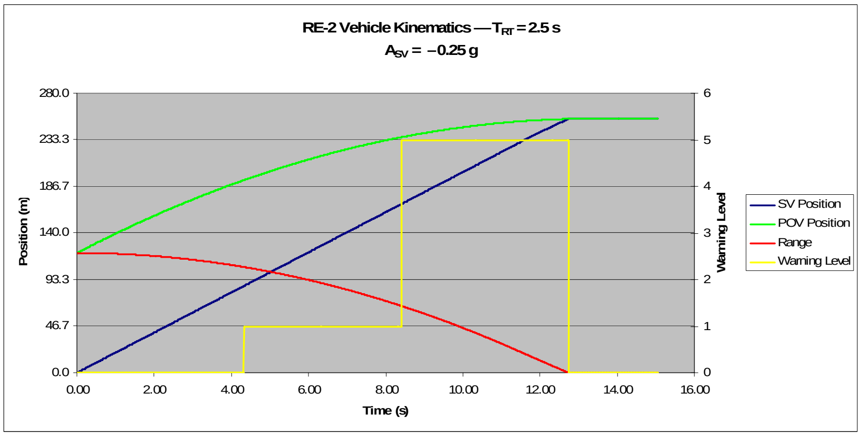


Figure B-6. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

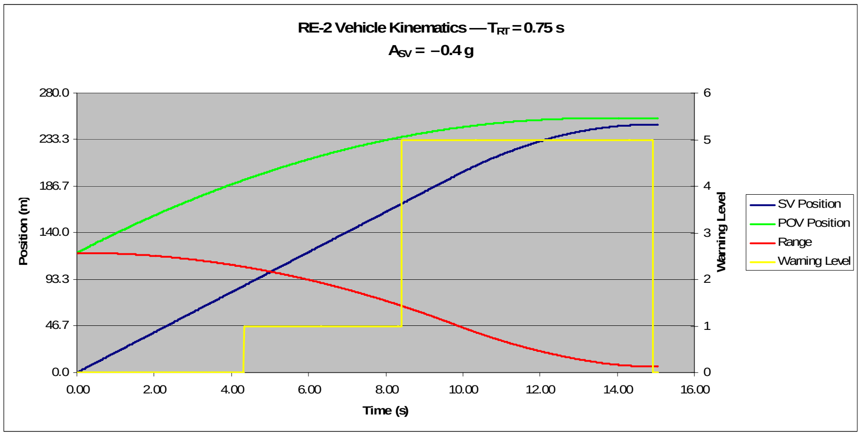


Figure B-7. Relationship between SV and POV as a function of RT (0.7.5s) and SV deceleration (-0.4g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

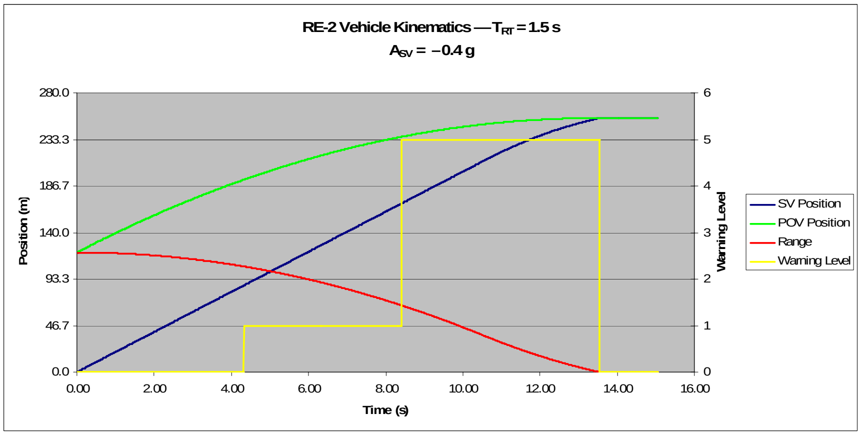


Figure B-8. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.4g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

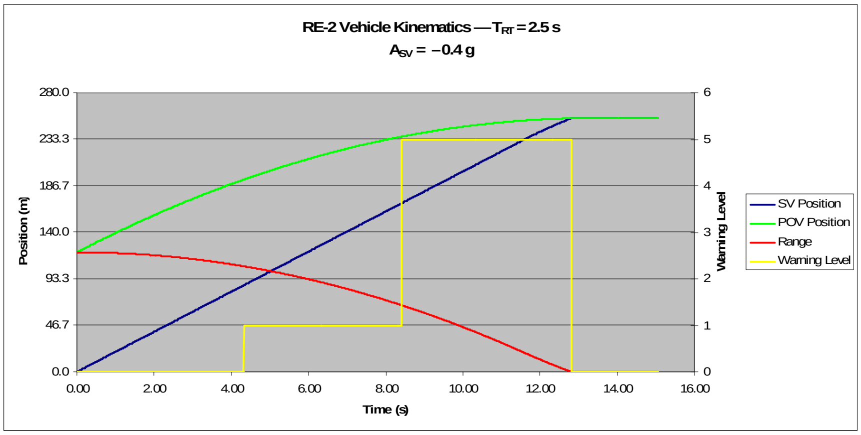


Figure B-9. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.4g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

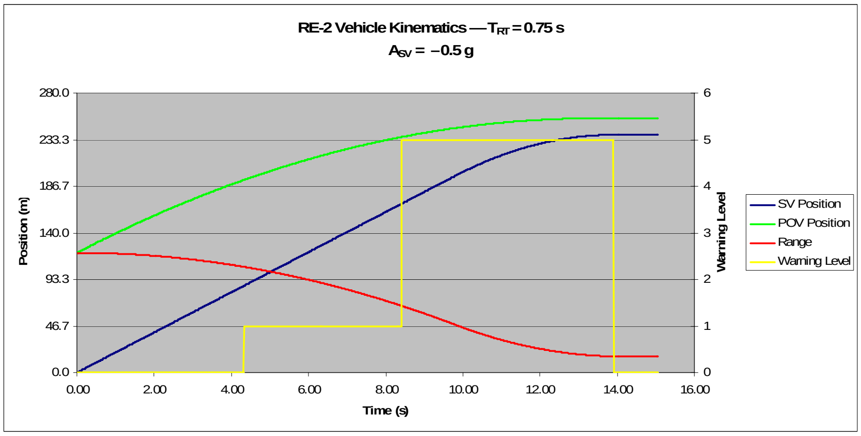


Figure B-10. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0. 5g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

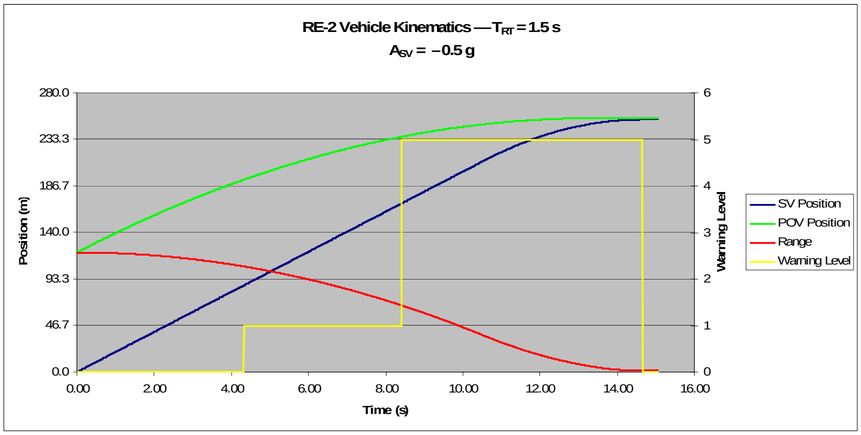


Figure B-11. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.5g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

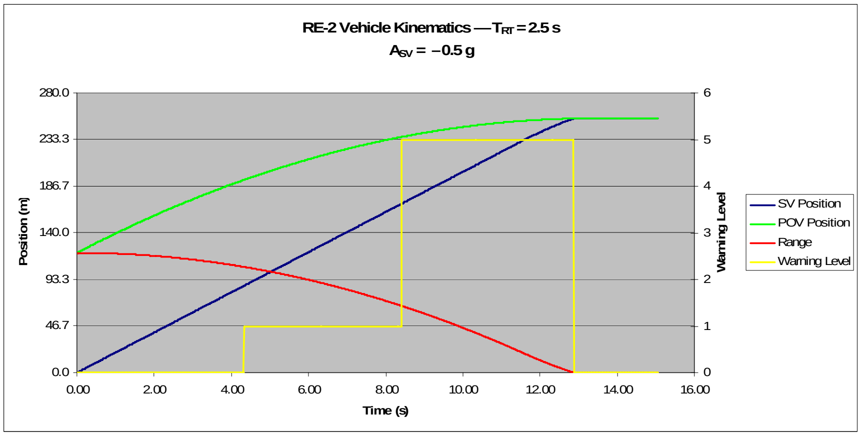


Figure B-12. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.5g) for RE-2: Rear-end conflict with slowing POV and a short time gap.

RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap

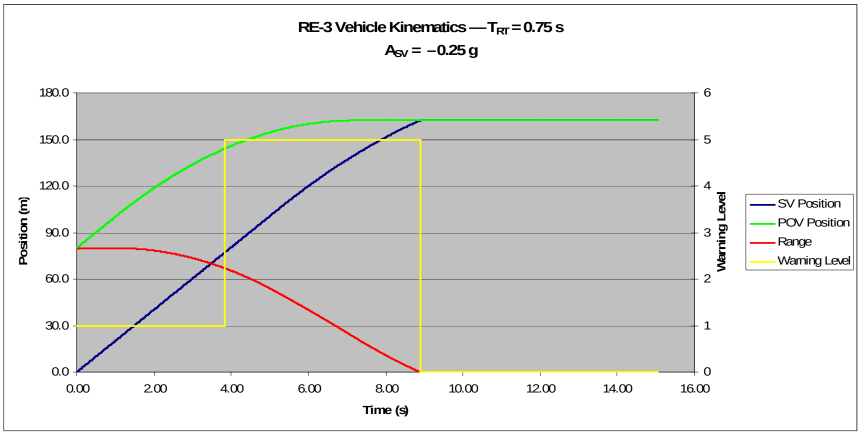


Figure B-13. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

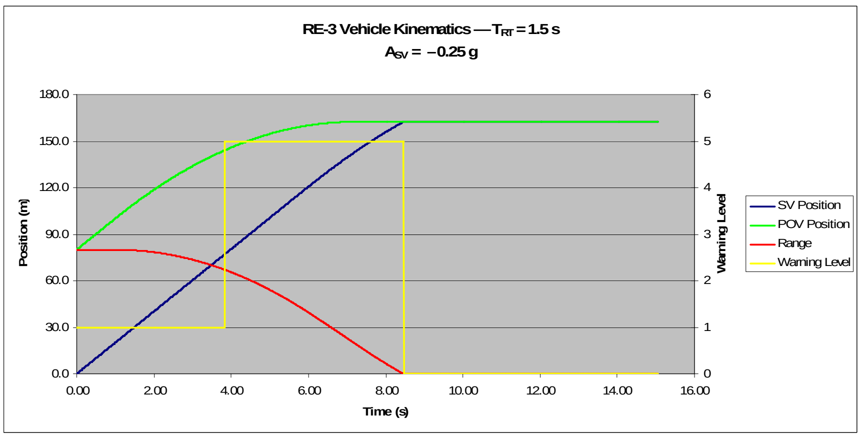


Figure B-14. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

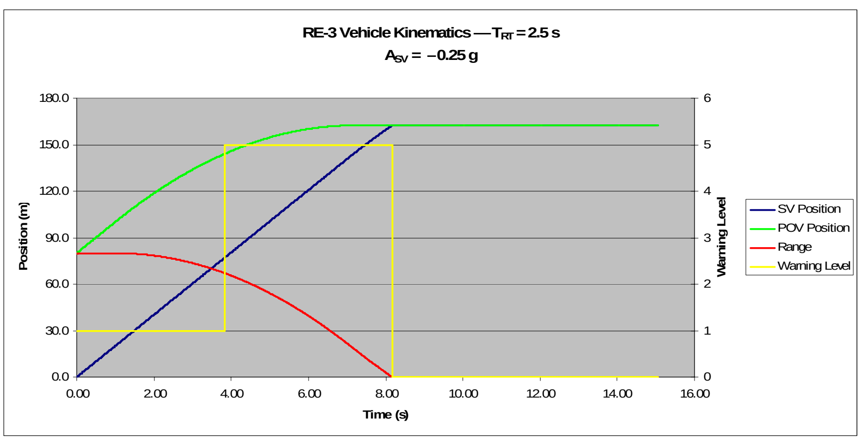


Figure B-15. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

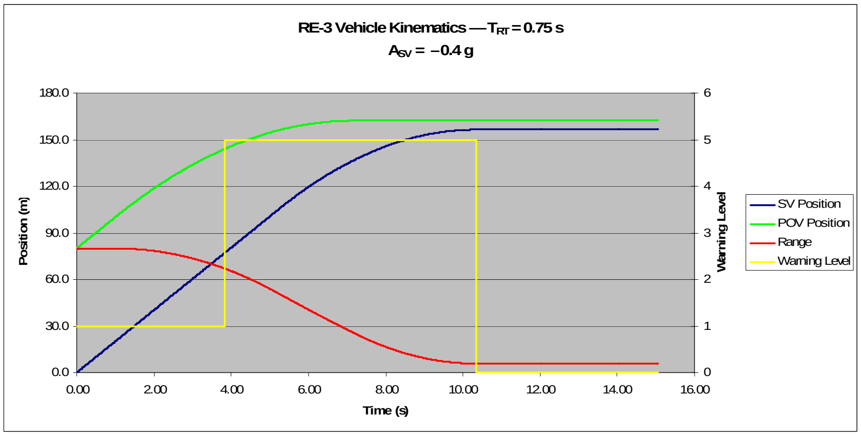


Figure B-16. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.4g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

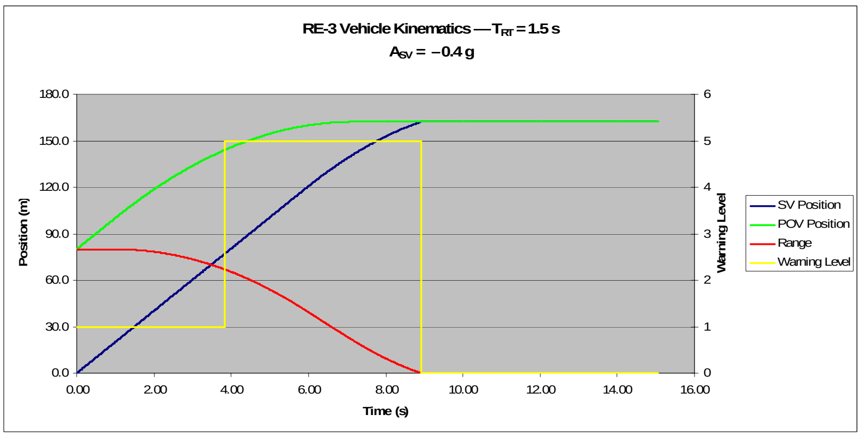


Figure B-17. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.4g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

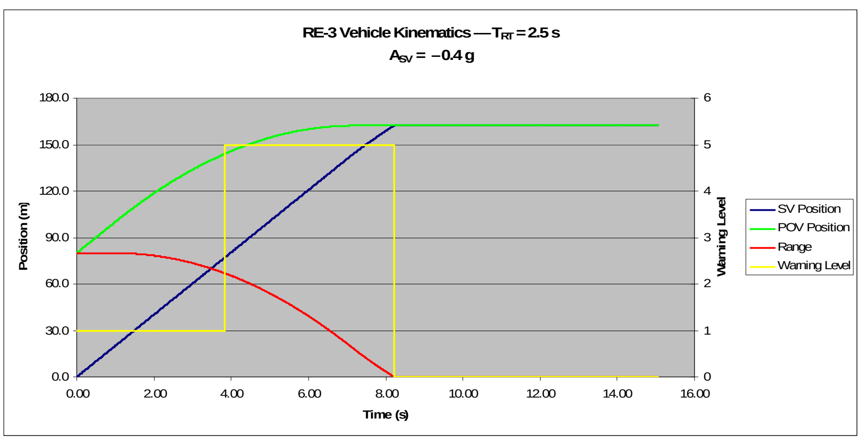


Figure B-18. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.4g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

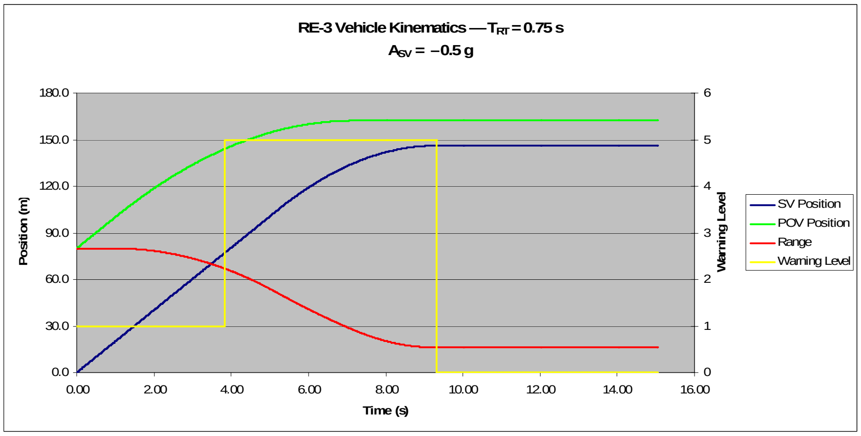


Figure B-19. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.5g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

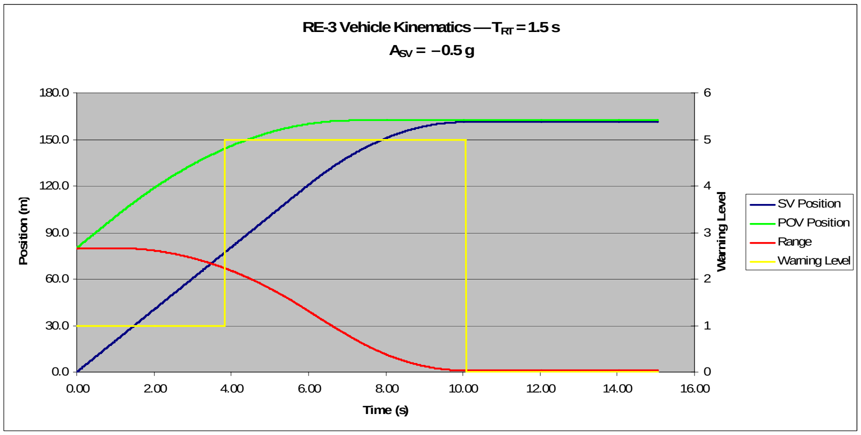


Figure B-20. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.5g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

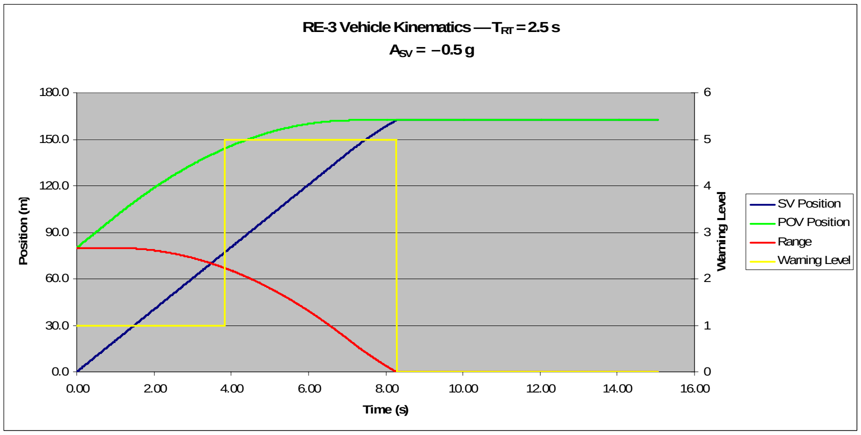


Figure B-21. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.5g) for RE-3: Rear-end conflict with an aggressively slowing POV and a long time gap.

RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap

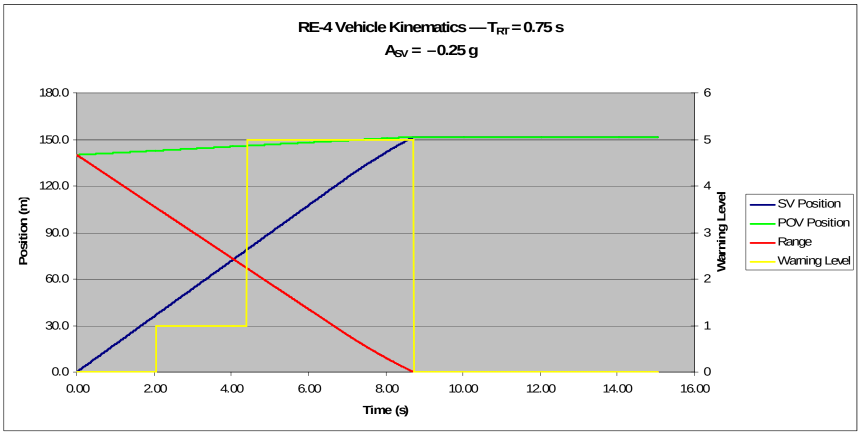


Figure B-22. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

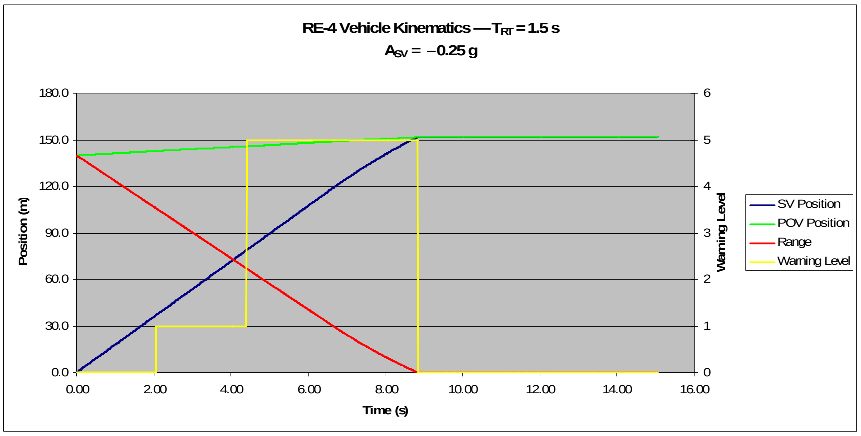


Figure B-23. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

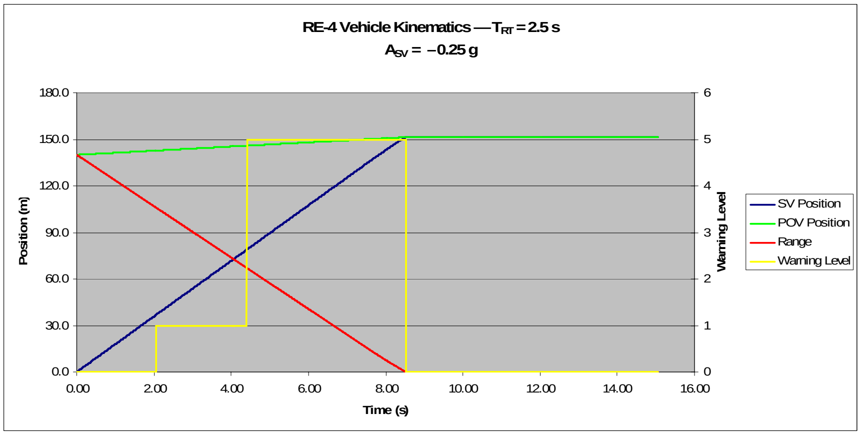


Figure B-24. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

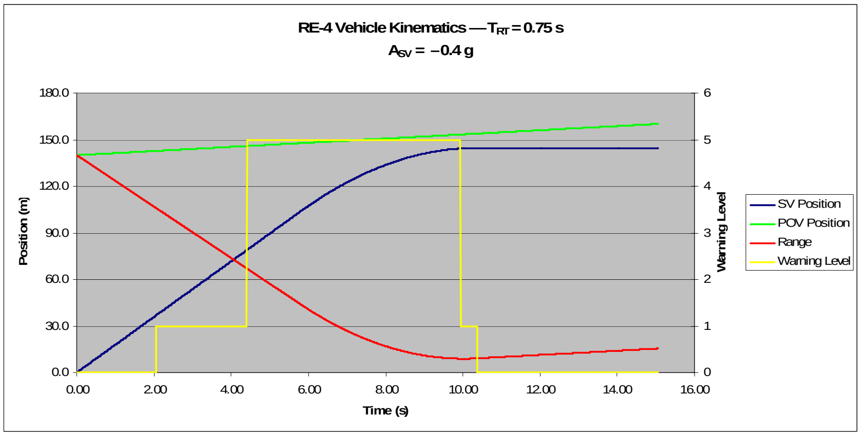


Figure B-25. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.4g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

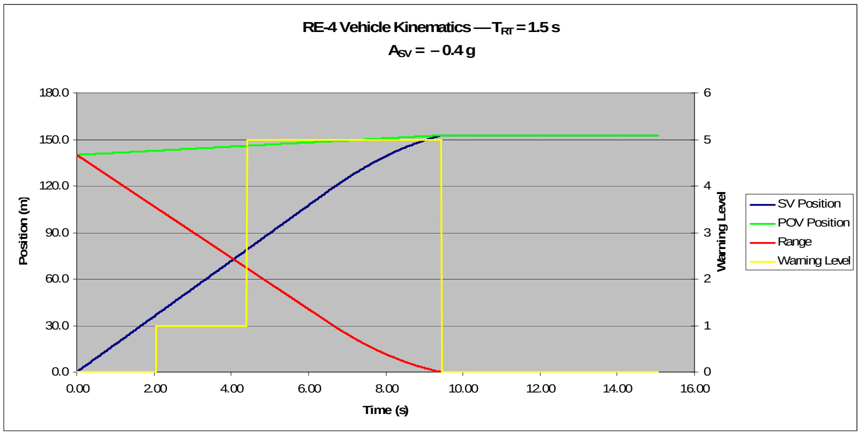


Figure B-26. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.4g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

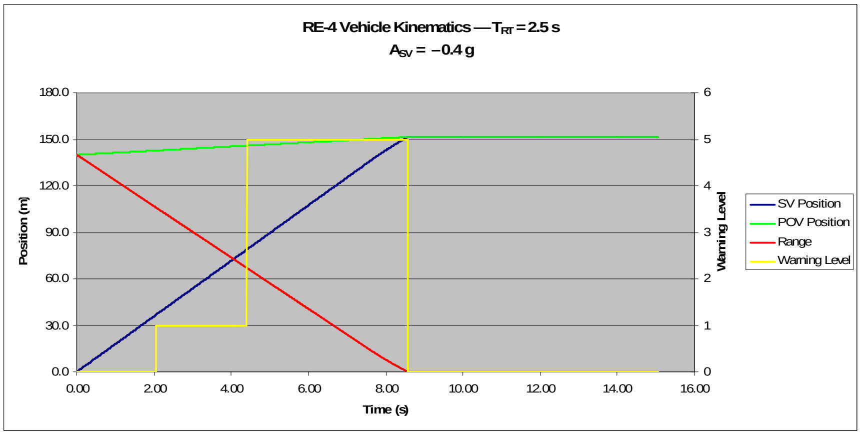


Figure B-27. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.4g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

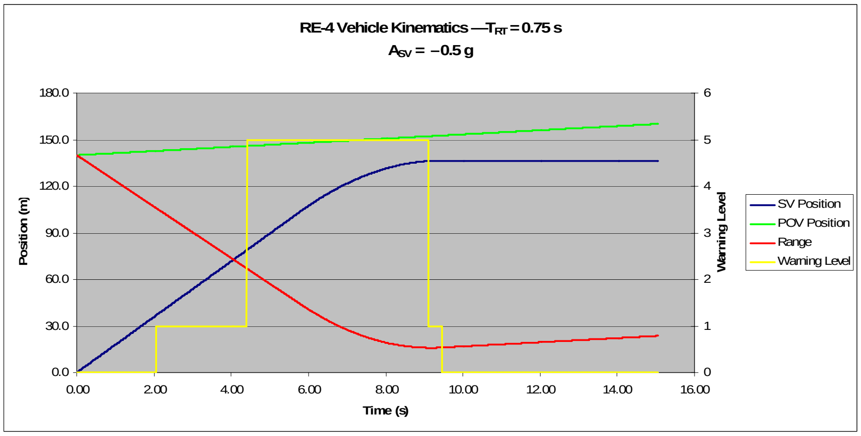


Figure B-28. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.5g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

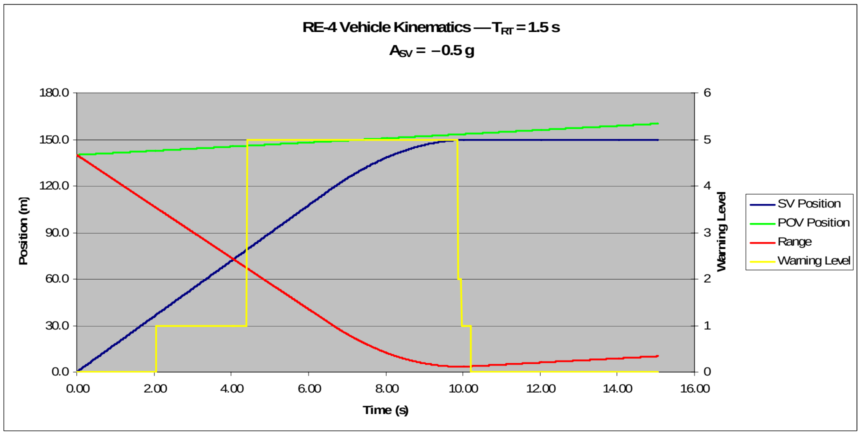


Figure B-29. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.5g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

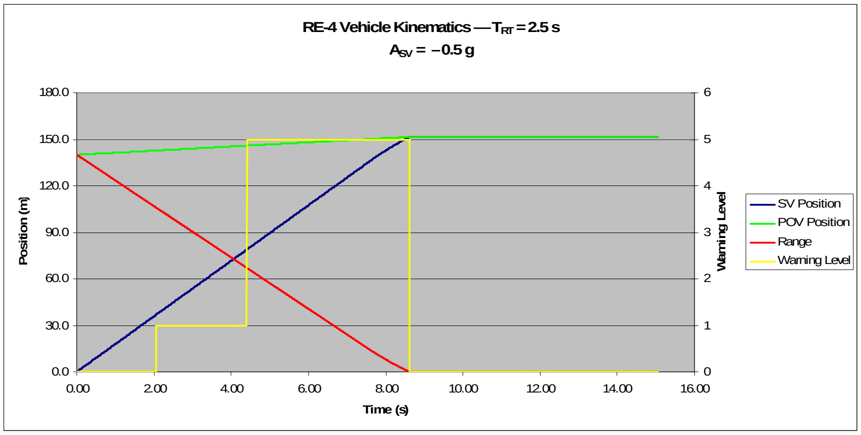


Figure B-30. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.5g) for RE-4: Rear-end conflict with slowing (nearly stopped) POV and a long time gap.

RE-5: Rear-end conflict with a slower POV after a lane change (aka Scenario 1.5)

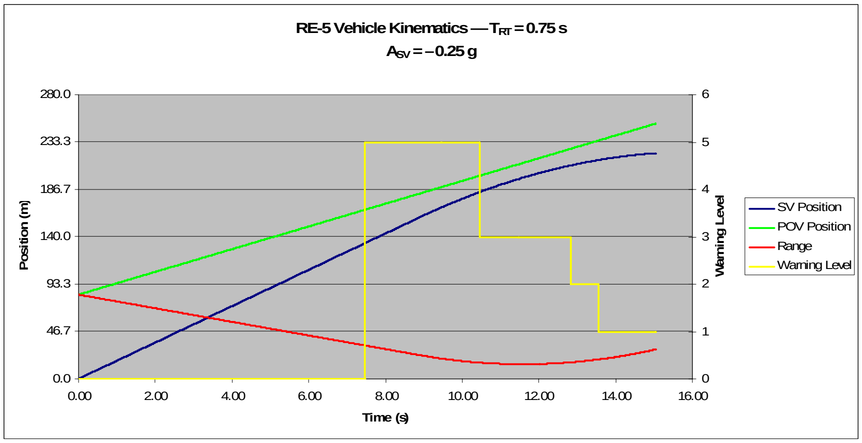


Figure B-31. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-5: Rear-end conflict with a slower POV after a lane change (aka Scenario 1.5).

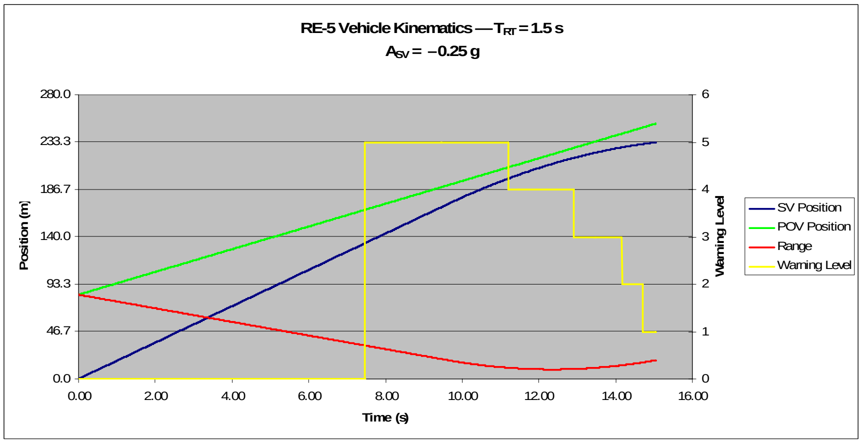


Figure B-32. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-5: Rear-end conflict with a slower POV after a lane change (aka Scenario 1.5).

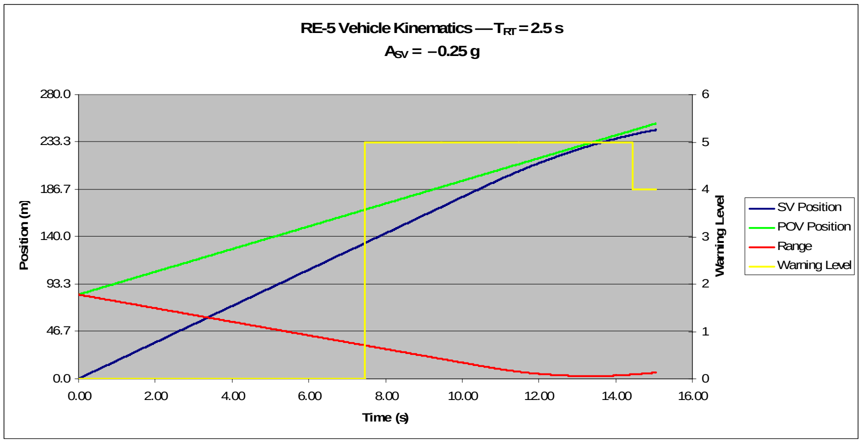


Figure B-33. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-5: Rear-end conflict with a slower POV after a lane change (aka Scenario 1.5).

RE-6: Rear-end conflict with POV after a cut-in by the POV (aka Scenario 1.6)

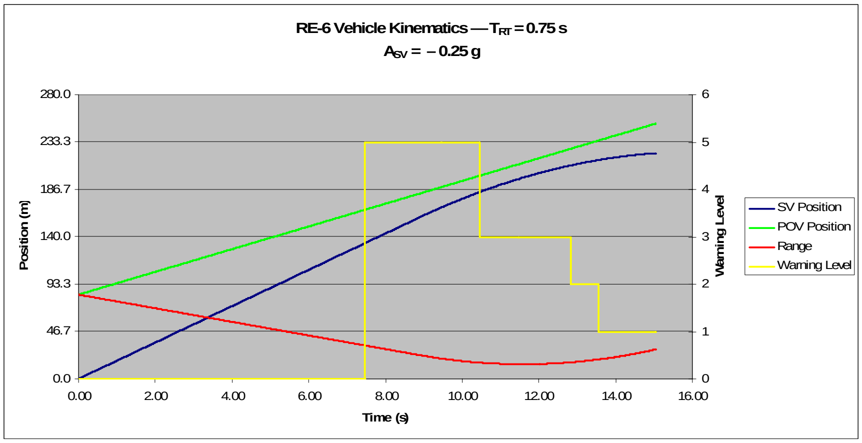


Figure B-34. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-6: Rear-end conflict with POV after a cut-in by the POV (aka Scenario 1.6).

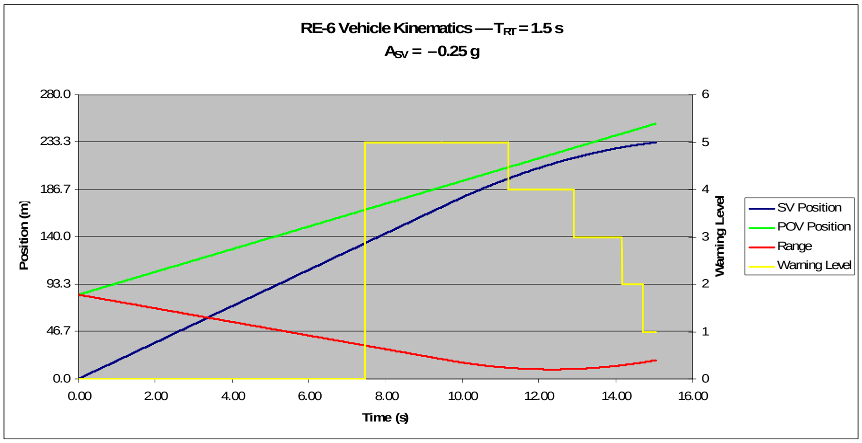


Figure B-35. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-6: Rear-end conflict with POV after a cut-in by the POV (aka Scenario 1.6).

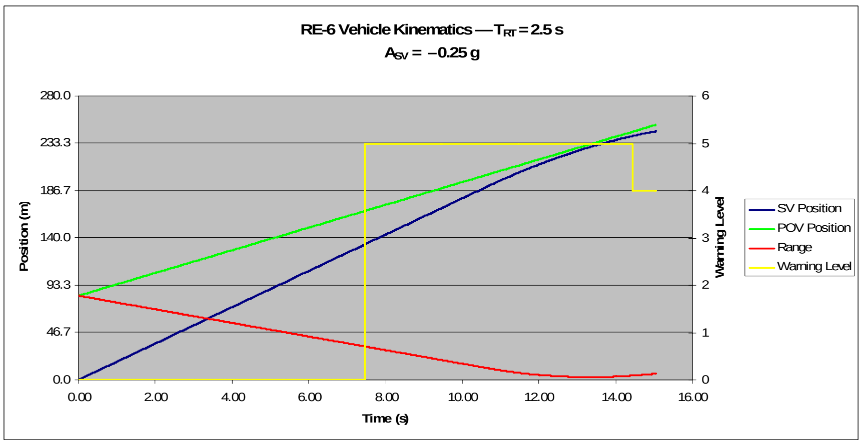


Figure B-36. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-6: Rear-end conflict with POV after a cut-in by the POV (aka Scenario 1.6).

RE-7: Rear-end conflict with a constant speed POV (motorcycle) (aka Scenario 1.7)

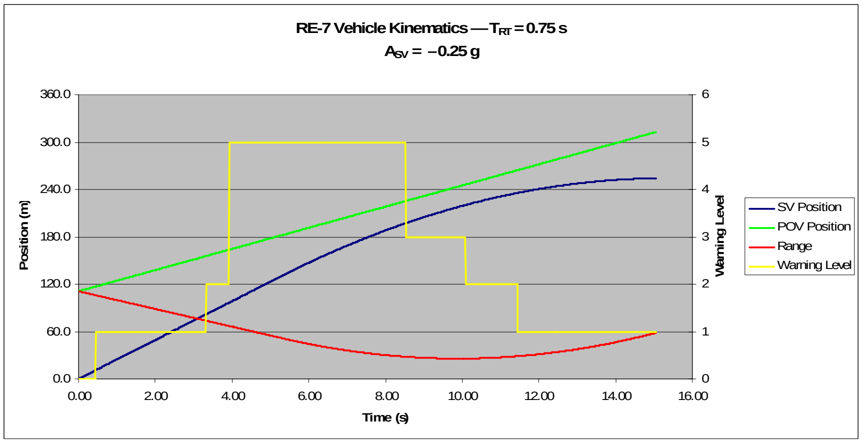


Figure B-37. Relationship between SV and POV as a function of RT (0.75s) and SV deceleration (-0.25g) for RE-7: Rear-end conflict with a constant speed POV (motorcycle) (aka Scenario 1.7).

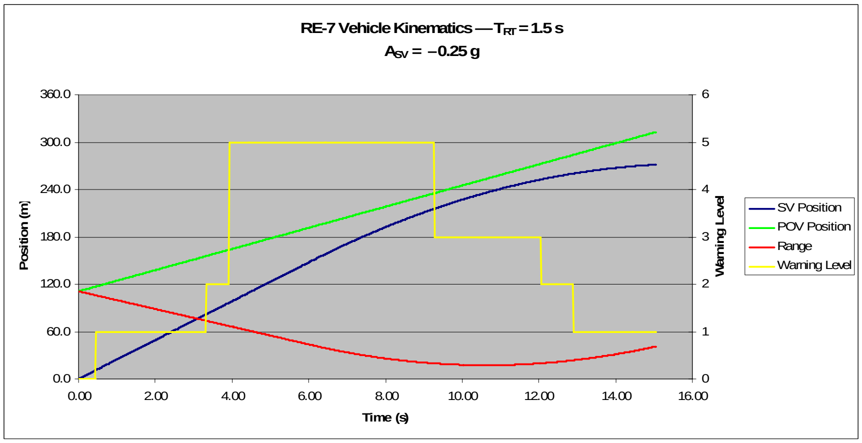


Figure B-38. Relationship between SV and POV as a function of RT (1.5s) and SV deceleration (-0.25g) for RE-7: Rear-end conflict with a constant speed POV (motorcycle) (aka Scenario 1.7).

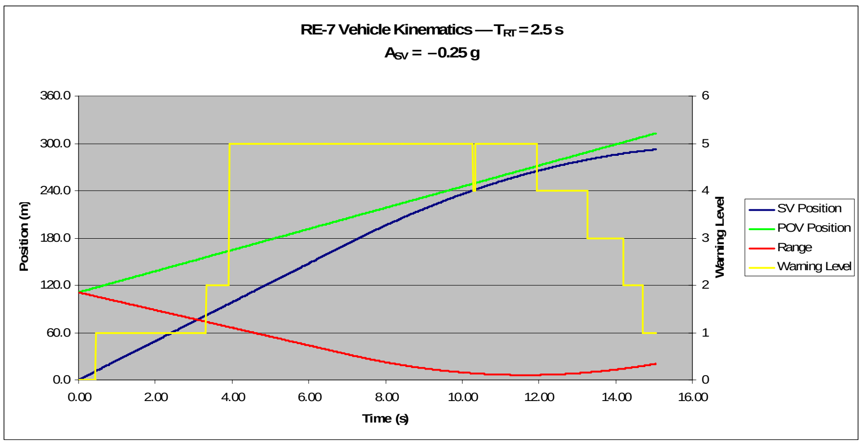


Figure B-39. Relationship between SV and POV as a function of RT (2.5s) and SV deceleration (-0.25g) for RE-7: Rear-end conflict with a constant speed POV (motorcycle) (aka Scenario 1.7).

Appendix C: Equations and Algorithms used in Predicting Vehicle Kinematics in Required Forward Collision Warning Objective Test Scenarios

Following are descriptions of the equations and algorithms used to determine the kinematics of each scenario. Table C-1 describes the variables used in these equations.

Table C-1. Description of variables.

Variable	Description
t	Time
t_d	Delay time (system delay + driver RT + braking latency)
T_{hw}	Time headway between vehicles
T	Elapsed time from start of scenario
x, x_s, x_p	Instantaneous vehicle position (general, SV, and POV respectively)
x_0, x_{s0}, x_{p0}	Initial vehicle position (general, SV, and POV respectively)
v_{s0}, v_{p0}	Initial SV and POV velocity, respectively
v_p	Instantaneous POV velocity
a_s, a_p	SV and POV acceleration, respectively (negative values imply deceleration)
R	Instantaneous range (distance between vehicles)
R_0	Initial range
R_d	Range at the delay time
R_a	Range after the delay time (during SV deceleration)
TTC	Time to Collision

General

The general equation for straight-line motion is used as a basis for all calculations and is given in its general form as:

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

Range (R)

Range at a given instant is the initial range plus the difference between the distances traveled by the two vehicles.

$$
\begin{aligned}
R &= R_0 + \left(\frac{1}{2}a_p t^2 + v_{p0}t\right) - \left(\frac{1}{2}a_s t^2 + v_{s0}t\right) \\
&= R_0 + \frac{1}{2}\left(a_p - a_s\right)t^2 + \left(v_{p0} - v_{s0}\right)t
\end{aligned}
$$

Time Headway (Thw)

Time headway is the time required for the SV to travel the range distance based on the instantaneous velocity of the SV.

$$
T_{hw} = \frac{R}{v_{s0}}
$$

Elapsed Time (T)

Elapsed time is the time from the start of the test scenario to the current step. This calculation uses the same equation as TTC evaluated with R0 = R0 – R and Rd = 0 (see TTC section below).

$$
T = TTC\Big|_{R_0 = R - R_0,\, R_d = 0}
$$

Delay Time (td)

Delay time is the sum of the system latency, the driver RT, and the braking initiation delay.

Time to Collision (TTC)

The following algorithm was used to determine the TTC.

1. Determine whether a collision occurs during the delay time.

   - Find the range at the end of the delay

$$R_d = \begin{cases} R_0 + (v_{p0} - v_{s0})t_d + \frac{1}{2}a_p t_d^2 & \text{, if } a_p \neq 0 \\ R_0 + (v_{p0} - v_{s0})t_d & \text{, if } a_p = 0 \end{cases}$$

   - If $R_d \leq 0$, a collision occurs during the delay period, and *TTC* is found by substituting t into t_d and solving for t when $R_d = 0$.

$$TTC = \begin{cases} \dfrac{(v_{s0} - v_{p0}) - \sqrt{(v_{p0} - v_{s0})^2 - 2R_0 a_p}}{a_p} & \text{, if } R_d \leq 0 \text{ and } a_p \neq 0 \\ \dfrac{R_0}{v_{s0} - v_{p0}} & \text{, if } R_d \leq 0 \text{ and } a_p = 0 \end{cases}$$

2. If $R_d > 0$, then either no collision occurs or a collision occurs after the delay period. In this case *TTC* is the sum of the delay time and the time at collision during SV deceleration.

   - Find the range at time t during deceleration (assuming t=0 at the start of deceleration)

$$R_a = \begin{cases} R_d + (v_{p0} - v_{s0})t + \frac{1}{2}(a_P - a_s)t^2 & \text{, if } (a_p - a_s) \neq 0 \\ R_d + (v_{p0} - v_{s0})t & \text{, if } (a_p - a_s) = 0 \end{cases}$$

   - *TTC* is found by solving for t when $R_a = 0$ and adding to it the delay time (td).

$$TTC = \begin{cases} t_d + \dfrac{(v_{s0} - v_{p0}) - \sqrt{(v_{p0} - v_{s0})^2 - 2R_d(a_p - a_s)}}{a_p - a_s} & \text{, if } (a_p - a_s) \neq 0 \text{ and } R_d > 0 \\ t_d + \dfrac{R_d}{v_{s0} - v_{p0}} & \text{, if } (a_p - a_s) = 0 \text{ and } R_d > 0 \end{cases}$$

- A collision does not occur if *TTC* is undefined due to a negative value in the radical or zero in the denominator, or when the SV is stopped and the initial range is positive (POV is ahead of the SV).

Verification

The results from these equations were verified by comparing the values against graphs of the vehicle positions over a ten second interval using the general motion equations below. Collision times were defined as the smallest time at which the two curves intersected.

$$x_s = \begin{cases} x_{s0} + v_{s0}(t - t_d) + \frac{1}{2}a(t - t_d)^2 & \text{, for } a \neq 0 \\ x_{s0} + v_{s0}t & \text{, for } a = 0 \end{cases}$$

$$x_p = \begin{cases} R_0 + v_{p0}t + \frac{1}{2}a_p t^2 & \text{, for } v_p \neq 0 \\ R_0 - \frac{v_{p0}^2}{2a_p} & \text{, for } v_p = 0 \end{cases}$$