U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA

Implementation of the Revised Safety Impact Methodology (SIM) Tool

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1. Report No. DOT HS 812 890	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Implementation of the Revised Safety Impact Methodology Tool		**5. Report Date** May 2021
		6. Performing Organization Code
7. Authors Mikio Yanagisawa, Michael Razo, Gerard Fairley, and Wassim G. Najm		**8. Performing Organization Report No.**
9. Performing Organization Name and Address John A. Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142		**10. Work Unit No. (TRAIS)** 11. OT-VNTSC-NHTSA-18-04
		11. Contract or Grant No. Inter-Agency Agreement DTNH22-13-V-00106 HS63A4
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Safety Impact Methodology (SIM) software tool is a suite of simulation modules designed to assess the safety effectiveness of crash avoidance systems based on cooperative vehicle-to-vehicle (V2V) communications and/or vehicle-based sensors such as radar. The tool uses a Monte Carlo simulation approach to estimate reductions in crashes and crash severity for specific pre-crash scenario types. The output of the SIM tool can be combined with external data on exposure and occupant injury to support analysis of overall harm reduction. The SIM tool uses an incremental time-step approach to model linear motion, turning movements, driver reactions, and warnings/actions from the crash avoidance system. Each module configures the simulation engine to address a specific type of pre-crash scenario, with a wide array of user-configurable parameters. The SIM tool implements pre-crash scenarios that are addressed by the V2V-based forward crash warning, intersection movement assist, left turn assist, blind spot/lane change warning, do not pass warning, and emergency electronic brake light safety applications. The tool also has the capability to simulate other priority pre-crash scenarios and applicable safely applications, such as drifting into opposite direction travel lanes. This report details the mathematical and computational basis for the SIM tool, including assumptions, theory of operation, kinematic equations, and detailed specifications of pre-crash scenarios.

17. Key Words Vehicle-to-Vehicle, V2V, pre-crash scenarios, light vehicles, Monte Carlo, kinematic, simulation, system effectiveness, benefits, safety impact, crash avoidance, crash reduction, crash severity, safety impact methodology		**18. Distribution Statement** Document is available to the public from the National Technical Information Service, www.ntis.gov.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 127	**22. Price**

Form DOT F 1700.7 (8-72)   **Reproduction of completed page authorized**

Table of Contents

List of Figures

List of Tables

List of Acronyms and Variables

a	acceleration
a_{AB1}	automatic deceleration level of stage 1
a_{AB2}	automatic deceleration level of stage 2
ACAT	Advanced Crash Avoidance Technology
a_{HV}	average deceleration of host vehicle
$a_{HV}(0)$	initial acceleration of HV prior to reaction time (conflict involving HV accelerating)
$a_{HV}(tR)$	braking of HV at and after reaction time (conflict involving HV accelerating)
a_{Lat}	lateral acceleration
$a_{Lon}(tR)$	longitudinal acceleration at and after reaction time
a_{RV}	average deceleration of remote vehicle
atR	reaction time
B_A	reduction in annual baseline target crashes in a scenario by an application
BSW/LCW	blind spot warning/lane change warning
CDS	Crashworthiness Data System
CF	closed-form
CPR	crash prevention ratio
CP^s	crash probability in driving conflict for pre-crash scenario, s
CP_{with}	crash probability when exposed to a driving conflict corresponding to a target scenario in treatment condition
$CP_{without}$	crash probability when exposed to a driving conflict corresponding to a target scenario in baseline condition
d	distance traveled
d_{HV}	distance traveled by HV
$d_{HV}(0)$	distance traveled by HV in acceleration phase prior to reaction time (conflict involving HV accelerating)
d_{HVLat}	a dimension to measure the lateral distance traveled by the HV
d_{HVLon}	a dimension to measure the longitudinal distance traveled by the HV
$d_{HV}(tR)$	distance traveled during reaction time
d_i	initial distances
d_{Lat}	lateral distance
d_{Lon}	longitudinal distance
DNPW	do not pass warning
ΔV [delta v]	change in velocity

d_p	passing distance
Drift/Man	Drift/Maneuver
d_{RV}	distance traveled by RV
d_s	stopping distance
E_A	exposure ratio
EEBL	Emergency Electronic Brake Light
EDR	Event Data Recorder
EM_{with}	exposure measure to a driving conflict corresponding to a target scenario in baseline (with system assistance) condition
$EM_{without}$	exposure measure to a driving conflict corresponding to a target scenario in baseline (without system assistance) condition
ER	Exposure Ratio
EX^s	exposure measure to driving conflict for pre-crash scenario, s
EW_{HV}	Host Vehicle effective width
FARS	Fatality Analysis Reporting System
FCW	Forward Crash Warning
GES	General Estimates System
h_{Lat}	host vehicle lateral distance
HV	Host Vehicle
IMA	Intersection Movement Assist
ITS	Intelligent Transportation System
IVBSS	Integrated Vehicle-Based Safety System
j	jerk
j(0)	initial jerk in LC (acceleration) prior to reaction time
j(tR)	counter jerk in LC at and after reaction time
LC	Lane Change
LC/Man	Lane Change/Maneuver
l_{RV}	length of RV
l_{HV}	length of HV
L_{HV}	host longitudinal distance
L_{RV}	remote longitudinal distance
L_{RV1}	remote1 longitudinal distance
LTA	Left Turn Assist
LTAP	Left Turn Across Path
LTAP/OD	Left Turn Across Path/Opposite Direction
LTAP/OD-M	Left Turn Across Path/Opposite Direction - Moving
LTAP/OD-S	Left Turn Across Path/Opposite Direction - Stopped

LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving at slower constant speed
LVS	Lead Vehicle Stopped
m_{HV}	mass of HV
m_{RV}	mass of RV
N_C	annual number of baseline target crashes in a scenario
NASS	National Automotive Sampling System
N^s	annual value of crashes in pre-crash scenario, s
OD/Man	Opposite Direction Maneuver
OD/No Man	Opposite Direction No Maneuver
R	range
r	turn radius of HV
$r1_{Lat}$	remote1 lateral distance
$R_{@Brake}$	range at brake onset
$RCCZ_{HV}$	range of HV to clear crash zone
R_{dot}	range rate or closing speed
R_{dotLon}	closing speed labeled as longitudinal direction only
R_{HV}	range of HV to intersecting paths
R_{HVLat}	HV initial distance
R_{init_D}	Initial distance if RV is struck when decelerating in LVD
R_{init_S}	Initial distance if RV is struck when stopped in LVD
$R_{initial}$	initial range
R_{RV}	range of RV to intersecting paths
R_{RVLat}	initial lateral distance
RV	Remote Vehicle
RV1	non-contact other remote vehicle
SCP	Straight Crossing Paths
SCP-M	Straight Crossing Paths - Moving
SCP-S	Straight Crossing Paths - Stopped
SE^s	System Effectiveness in pre-crash scenario, s
SIM	Safety Impact Methodology
Tt	time
t_i	initial reaction times
tR	reaction time
tR_{HV}	host reaction time
tR_{RV}	remote reaction time

tRSteer	host steering reaction time
ts	time step in iterative loop
TTC	Time-to-Collision
TTC(0)	Time-to-Collision @ Trigger
TTC_{AB1}	TTC activation of autobrake 1
TTC_{AB2}	TTC activation of autobrake 2
TTC_{Decel}	Time-to-Collision calculation if RV is struck when decelerating in LVD
$TTC_{Stopped}$	Time-to-Collision calculation if RV is struck when stopped in LVD
$TTCZ_{HV}$	time for HV to clear crash zone
$TTCZ_{RV}$	time for RV to clear crash zone
TTEL	Time to equal longitude
TTI	time to intersecting paths
$TTRZ_{HV}$	time for HV to reach crash zone
$TTRZ_{RV}$	time for RV to reach crash zone
v	velocity
V2V	Vehicle-to-Vehicle
v_{HV}	host vehicle velocity (initial)
$v_{HV}(0)$	initial low speed of HV at the start of conflict (conflict involving HV accelerating)
a_{HVLat}	lateral acceleration of HV
v_{HVLat}	lateral velocity of HV
v_{HVLon}	longitudinal velocity of HV
$v_{HV}(tR)$	HV velocity reached in acceleration phase until reaction time (conflict involving HV accelerating)
v_{Lat}	lateral speed
v_{Lon}	longitudinal speed
vR_{Lon}	remote longitudinal speed
$vR1_{Lon}$	remote1 longitudinal speed
v_{RV}	remote vehicle velocity
W_{HV}	host vehicle width
W_{RV}	remote vehicle width
XX1	host reaction Boolean condition X
YY1	host reaction Boolean condition Y

PREFACE

The Volpe National Transportation Systems Center, in support of the National Highway Traffic Safety Administration, has developed and applied a safety impact methodology (SIM) tool to estimate the safety benefits of crash warning applications for light vehicles based on vehicle-to-vehicle (V2V) communications under a multi-year, multi-task intra-agency agreement. This agreement includes the tasks to develop, program, and document the SIM tool; identify performance measures and determine preliminary performance requirements; devise test procedures and run tests to characterize the performance of prototype systems; conduct an independent evaluation of crash warning applications from the Safety Pilot Model Deployment field operational tests; and exercise the SIM tool using the results from the Safety Pilot Model Deployment and additional data sources to estimate the potential safety benefits for V2V safety applications.

This report describes the mathematical and computational basis for the SIM tool, including assumptions, theory of operation, kinematic equations, and detailed specifications of pre-crash scenarios. In addition to this report, companion reports on V2V crash warning applications for light vehicles are available that document the approach and results of safety benefits, characterization test procedures, performance measures, and independent evaluation of the Safety Pilot Model Deployment.

Executive Summary

This report describes the operational design and implementation of the revised SIM (Yanagisawa et al., in press) with a computer-based simulation tool, which supports the projection of national safety benefits of motor vehicle crash avoidance systems using cooperative V2V communications and/or vehicle-based sensors, such as radar.

Safety benefits are expressed by the potential number of crashes that could be avoided and the number of injured persons that could be reduced with the use of these systems. The SIM tool was developed based on findings from the Advanced Crash Avoidance Technology program under National Highway Traffic Safety Administration research. In this program, four teams from the automobile industry, and university experts, were tasked to exercise the concepts of the SIM framework for various pre-crash scenarios.

The SIM tool produces probability of crash estimates for specific pre-crash scenarios and resulting impact speeds from crashes. It specifically estimates the crash prevention ratio (the ratio of crashes with system assistance versus those without system assistance) using crash and non-crash data about driver exposure and response to driving conflicts/pre-crash scenarios. Data sources include, but are not limited to, field operational tests; controlled experiments on test tracks and in driving simulators; historical crash data; and previous research. Using the Monte Carlo method, the SIM tool simulates a driving conflict with and without the assistance of a crash avoidance application and determines the outcome, crash or no crash, as well as the impact speed and delta V (ΔV) in cases where a crash occurs. Simulation results can then be used to derive system effectiveness in terms of reductions in crashes and injured persons.

The SIM tool uses pre-defined pre-crash scenarios from crash data, real-world crash data, and associated kinematics to construct conflicts and run kinematic simulations. The initial SIM tool implemented the following six target pre-crash scenarios for four selected V2V safety applications:

1. Straight Crossing Paths – Intersection Movement Assist,
2. Left turn across path/opposite direction – Left Turn Assist,
3. Change lanes/same direction – Blind Spot Warning/Lane Change Warning,
4. Lead vehicle moving at constant speed – Forward Crash Warning (FCW),
5. Lead vehicle decelerating – FCW, and
6. Lead vehicle stopped – FCW.

The initial SIM tool was revised to implement additional priority pre-crash scenarios and potential V2V safety applications:

7. Opposite direction/passing maneuver – Do Not Pass Warning (DPNW),
8. Opposite direction/no maneuver, and
9. Longitudinal queue (a series of rear-ends) – Emergency Electronic Brake Light (EEBL)

Although the SIM tool was developed primarily to research V2V safety applications using the above eight pre-crash scenarios, the tool could be used to assess other technologies, such as vehicle-based (e.g., radar- and/or video-based) crash avoidance systems. Furthermore, the SIM tool was built to be flexible and robust so that new pre-crash scenarios can be added, or existing pre-crash scenarios and countermeasures can be modified.

At the core of the SIM tool is a highly customizable simulation engine for vehicle kinematics. The engine uses an incremental time-step approach to model two-dimensional linear motion, turning movements, driver reactions, and warnings/actions from the crash avoidance system. Each module configures the

simulation engine to address a specific type of pre-crash scenario, with an array of data input parameters (e.g., driver reaction time, driver response level, and system activation points). These parameters can be defined by the user through a probability distribution that reflects the input parameter's occurrence. The simulation is repeated for a user-specified number of runs using the pre-defined input parameters. The outcomes of all runs are then aggregated into the final results.

This report details the mathematical and computational basis for revised the SIM tool, including assumptions, theory of operation, kinematic equations, and detailed specifications of pre-crash scenarios.

1   Introduction

This report describes an implementation of the safety impact methodology (SIM) with a computer-based simulation tool (SIM tool), which supports the projection of potential safety benefits for motor vehicle crash avoidance systems based on cooperative vehicle-to-vehicle (V2V) communications and/or vehicle-based sensors such as radar, lidar, and cameras. Safety benefits are expressed by the potential number of crashes that could be avoided, and the number of injured persons that could be reduced, with the use of these systems. The SIM tool produces probability of crash estimates for specific pre-crash scenarios and impact speeds for resulting crashes. Outputs from the SIM tool support the calculation of the system's crash avoidance and injury reduction effectiveness. The SIM estimates the safety effectiveness of crash avoidance systems using non-crash data about driver exposure and response to driving conflicts/pre-crash scenarios, which can be collected from field operational tests, controlled experiments on test tracks and driving simulators, and other sources (Najm & daSilva, 2000, Najm, daSilva, & Wiacek, 2000).

The National Highway Traffic Safety Administration, in cooperation with the automobile industry and university experts, have performed a number of projects under the Advanced Crash Avoidance Technology (ACAT) research program to project the potential safety benefits for near-term pre-production crash avoidance systems based on vehicle-based sensors (Funk et al., 2011). These projects explored various means to implement the SIM using computer simulations of a common framework. This report delineates the SIM implementation using a similar framework and focuses on pre-crash scenarios that are addressed by crash avoidance systems or safety applications based on V2V communications. The Volpe National Transportation Systems Center exercised this SIM implementation to estimate the safety effectiveness of the Intersection Movement Assist (IMA) and Left Turn Assist (LTA) safety applications by NHTSA (82 Fed. Reg. 3854).

1.1   Safety Impact Methodology

The SIM estimates the safety benefits in terms of the number of crashes that could potentially be avoided with the safety applications for an individual pre-crash scenario (Najm & daSilva, 2000):

$$\mathbf{B_A = N_C \times E_A} \tag{1}$$

> $\mathbf{B_A} \equiv$ Reduction in annual baseline target crashes in a pre-crash scenario by an application
> $\mathbf{N_C} \equiv$ Annual number of baseline target crashes in a pre-crash scenario
> $\mathbf{E_A} \equiv$ Crash avoidance effectiveness of an application in its target pre-crash scenario

The annual number of crashes, N_C, can be determined from historical crash databases such as the General Estimates System (GES) and the Fatality Analysis Reporting System (FARS). Crash avoidance system effectiveness is estimated based on the following set of equations:

$$\mathbf{E_A} = 1 - \text{Exposure Ratio} \times \text{Crash Prevention Ratio} \tag{2}$$

where the exposure ratio expresses the reduction in probability of exposure to a given pre-crash scenario, and crash prevention ratio expresses the reduction in crash probability. Equation **(2)** can be revised as follows:

$$E_A = 1 - \frac{EM_{with}}{EM_{without}} \times \frac{CP_{with}}{CP_{without}} \tag{3}$$

$EM_{with} \equiv$ Exposure Measure to a driving conflict corresponding to a target pre-crash scenario in treatment (with system assistance) condition

$EM_{without} \equiv$ Exposure Measure to a driving conflict corresponding to a target pre-crash scenario in baseline (without system assistance) condition

$CP_{with} \equiv$ Crash Probability when exposed to a driving conflict corresponding to a target pre-crash scenario in treatment condition

$CP_{without} \equiv$ Crash Probability when exposed to a driving conflict corresponding to a target pre-crash scenario in baseline condition

The ratio of <u>exposure measures</u>, *with* versus *without* system assistance, also known as the exposure ratio (ER), is the ability of a crash avoidance system to reduce the occurrence of conflicts in normal driving behavior (McMillan et al., 2001). Driving conflicts correspond to the kinematics of target pre-crash scenarios. An exposure to a conflict is counted when the movements of the host vehicle (HV) and the remote vehicle (RV) match the configuration of the conflict and the two vehicles are on a crash course if no avoidance action is taken by either vehicle. Estimates for ER may be determined from various sources, such as naturalistic driving field operational tests and human factors testing.[1]

The ratio of <u>crash probabilities</u>, *with* versus *without* system assistance, also known as the crash prevention ratio (CPR), is the ability of a crash avoidance system to reduce the likelihood of a crash given that a vehicle enters a conflict (McMillan et al., 2001). The crash probability accounts for whether the HV will crash with the RV in a driving conflict despite its crash avoidance action, such as braking. The SIM tool specifically estimates CPR as detailed in subsequent sections.

As an example to illustrate ER in a lane-change pre-crash scenario, consider an HV intending to make a lane change onto an adjacent lane which the RV currently occupies. A warning application may alert the HV to the presence of the RV in the adjacent lane, and deter the HV from attempting the lane change. Without this warning application, the HV may attempt this lane change and enter into a conflict. The ability of the application to reduce the likelihood of the HV entering such lane-change conflicts is represented by ER. The CPR represents the ability of the warning application to help avoid a crash once the HV has entered this lane-change conflict.

However, in conflicts where a crash occurs, system effectiveness can be derived from the ability of the application to reduce the resulting severity of the crash, therefore reducing the potential injury to occupants involved (Najm, daSilva, & Wiacek, 2000). This can be achieved by improving driver reaction in terms of time or magnitude (i.e., reaction time and braking force) or automated control (i.e., automatic braking and brake assist). The SIM tool reports distributions for impact speed and delta V (ΔV) measures from simulated crashes to determine crashworthiness and system effectiveness, based on reductions of these measures. ΔV is a crash severity measure denoting the instantaneous change in speed that a vehicle undergoes during a crash. Detailed information on this is provided in further sections.

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[1] These are suggested data sources for ER. Valid ER estimates are dependent on test conditions and data available. Other data sources may exist and can be applied to the benefits equation.

1.2   Advanced Crash Avoidance Technology Program

The ACAT program tasked four teams to design an approach to implement the SIM framework for near-term pre-production safety systems (Funk et al., 2011). Figure 1 illustrates the SIM framework that communicates NHTSA's operational vision of a SIM tool. The elements of the SIM framework include activities, functions, and interactions. This framework can be adjusted to accommodate and communicate various approaches. This report focuses on the implementation of the *Model Creation* and *Data Generation* blocks.

Volpe developed the SIM tool, a personal computer-based simulation program, which contains several kinematic modules, depicting specific pre-crash scenarios. The tool allows the user to select and create the initial conditions of a target pre-crash scenario, simulate the pre-crash scenario with driver/vehicle performance data, and store the output of the simulation – including crash probability, impact speed, and ΔV. The user is then able to analyze the results of the computer simulation, outside the tool, to determine the safety benefits for crash avoidance systems in terms of reductions in the number of crashes and related injured persons. Volpe developed its SIM tool in cooperation with NHTSA to evaluate the effectiveness of V2V-based crash avoidance systems in support of NHTSA's V2V Readiness Report (82 Fed. Reg. 3854).
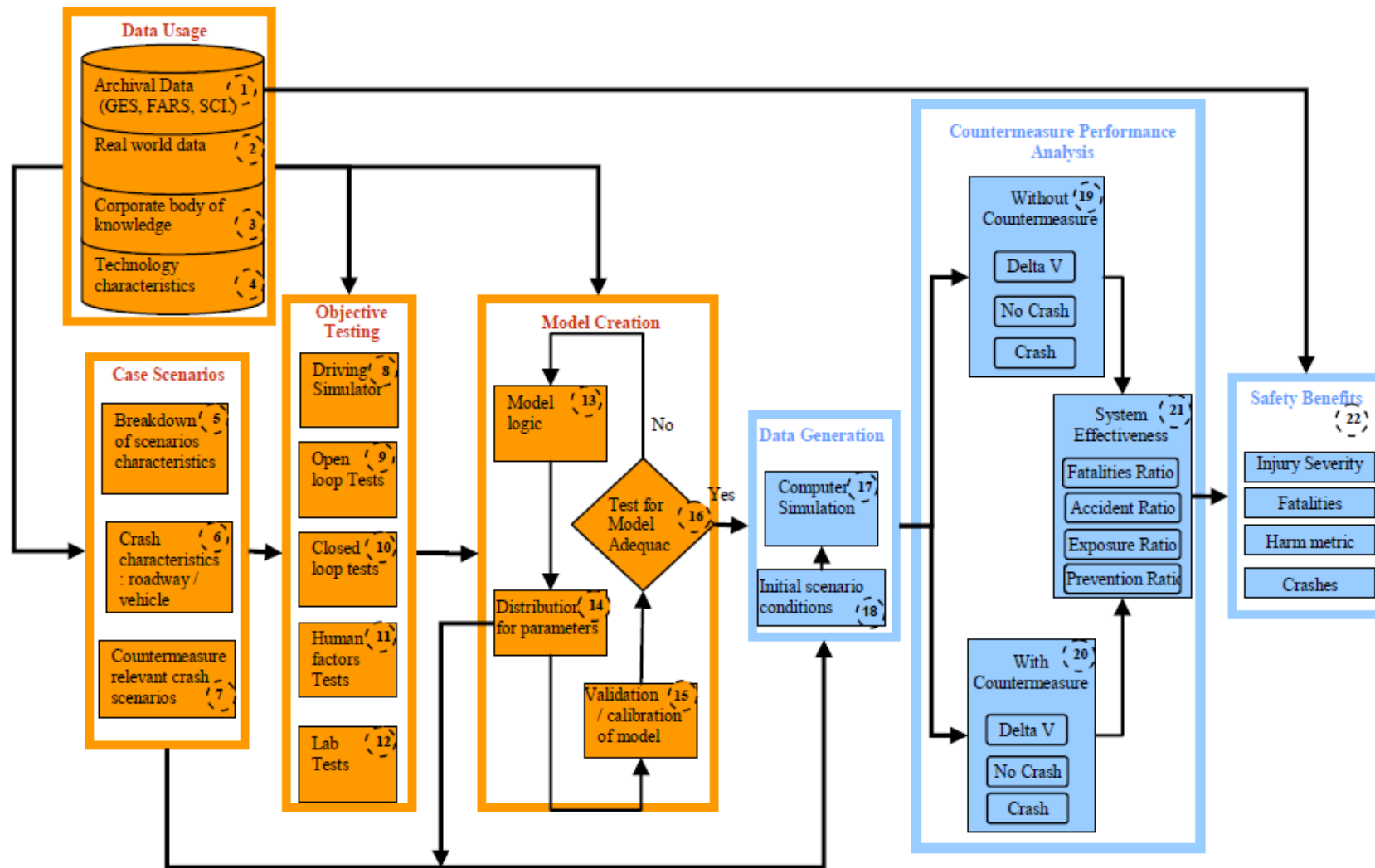
Figure 1. SIM Implementation Framework

2   Tool Pre-Crash Scenarios, Data Sources, and Assumptions

The SIM tool was initially developed for V2V safety applications and focused on pre-crash scenarios that could benefit from this technology.[2] The SIM tool uses these pre-defined pre-crash scenarios and associated kinematics to construct conflicts and run kinematic simulations.

2.1   Pre-Crash Scenarios and Safety Applications

The SIM tool estimates the effectiveness of safety applications that are designed to inform the driver with an advisory message about driving conflicts, warn the driver of an imminent crash, and/or apply automatic controls such as braking. Each safety application addresses a specific pre-crash scenario.

Figure 2 illustrates the average annual crash frequency of the 10 priority pre-crash scenarios addressed by V2V-based safety applications (Najm et al., 2013). The initial SIM tool addressed 6 of the top 10 pre-crash scenarios (Yanagisawa et al., in press):

1. Straight crossing paths (SCP) at non-signal, addressed by the IMA application.
2. Left turn across path/opposite direction (LTAP/OD), addressed by the LTA application.
3. Lead vehicle stopped (LVS), addressed by Forward Crash Warning (FCW) application.
4. Lead vehicle moving at constant speed (LVM), addressed by FCW.
5. Lead vehicle decelerating (LVD), addressed by FCW.
6. Change lanes/same direction, addressed by the blind spot warning/lane change warning (BSW/LCW) application.

The SIM tool has been revised to implement two more of the top 10 pre-crash scenarios and a modification of the rear-end pre-crash scenario:

7. Opposite direction/passing maneuver, addressed by the do not pass warning (DNPW) application.
8. Opposite direction/no maneuver.[3]
9. Rear-end longitudinal queue, addressed by the emergency electronic brake light (EEBL) application.

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[2] The SIM tool was also developed to permit expansion of new pre-crash scenarios and countermeasures, as well as modifications of existing pre-crash scenarios and countermeasures. Expansion and modification of the SIM tool will aid in the assessment of other safety systems (production, near-term, and prototype).

[3] No current V2V application addresses the opposite direction/no maneuver pre-crash scenario. No maneuver assumes a unintentional drift.
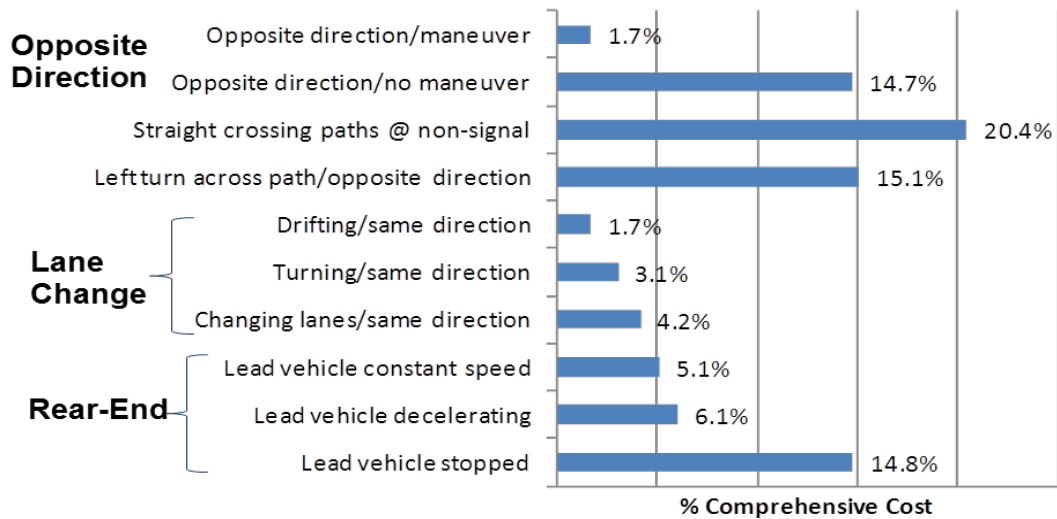
Figure 2. Priority Pre-Crash Scenarios and Associated Comprehensive Cost Percentage

Individual modules were developed to address the various V2V applications, which are detailed in subsequent sections. Although the SIM tool was developed to incorporate five V2V safety applications for the eight pre-crash scenarios, the individual modules have the capability to assess other technologies (if applicable), including radar- and/or video-based crash avoidance systems. Furthermore, the modular design allows the SIM tool to evaluate other emerging safety applications for pre-crash scenarios that are not discussed here.

2.2 Data Sources

Data sources are crucial to determining accurate input parameters for use in the SIM tool, building crash-imminent conflict scenarios, and estimating system effectiveness. The SIM tool uses conflict, driver, vehicle, and system performance data to develop pre-crash scenarios, simulate the pre-crash conflict, and output results. The SIM tool was developed to incorporate multiple data sources to estimate various effectiveness ranges. Potential data sources may include, but are not limited to, historical crash data, field test data, characterization test data, and relevant data found in the literature.[4]

2.2.1 Historical Crash Data

Historical crash data, such as the GES, Crashworthiness Data System (CDS), and FARS, can be used to determine the size of the crash problem. Analyses of nationally representative crash databases identify the target population as well as aid in the characterization of the pre-crash scenarios. Characterization can include travel speeds, environmental conditions, vehicle motion, or driver responses. Details surrounding the pre-crash scenario allow for an accurate depiction of the conflict within the SIM tool's kinematic modules and better system effectiveness estimates.

Event data recorder (EDR) information, when available, can also be used to supplement historical crash data to help determine an accurate range of pre-crash conditions and movements.

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[4] Data sources listed and described in this report are suggested data sources for input into the SIM tool. Other data sources may provide statistically significant data and can be adapted for input into the SIM tool. The SIM tool is used to create repeatable and safety-critical driving conflicts, which may result in a crash, for analysis and input into the safety benefits equation.

2.2.2 Field Test Data

Naturalistic driving data from field operational tests provides a plethora of driver performance data in normal driving conditions, both with and without a crash avoidance system in place. Field test data can determine reaction times or braking levels in various driving scenarios, both in normal driving and conflict scenarios. Naturalistic driving also gives detailed information on the occurrence of conflict scenarios, *with* and *without* a crash avoidance system. System effectiveness can be calculated from the reduction in observed conflicts. Field test data may also provide information on true and false system activation rates, as well as driver acceptance, for use in the analysis of system effectiveness.

Completed field tests, such as the Integrated Vehicle-Based Safety System (IVBSS) (Nodine et al., 2011) test deployment, can be leveraged to analyze naturalistic driving. The Intelligent Transportation System (ITS) V2V safety applications research program conducted research on the use, and driver acceptance of, V2V safety applications in the Safety Pilot Model Deployment, conducted in a small-scale cooperative real-world environment (Najm & Tuttle, 2010).

2.2.3 Characterization Test Data

Characterization tests measure participant or system responses to crash-imminent conflicts without bias or preemptive knowledge of an upcoming conflict beyond immediate observational capabilities. These tests can be conducted on test tracks or in appropriate driving simulators.

Characterization tests provide information on:

- System performance capabilities, including timing of system actions, range of activation (speed/distance), false activations, and availability. The ITS V2V research team also conducted characterization tests to measure the performance of prototype V2V safety applications.
- Driver response, including response type, reaction times, and magnitudes. Controlled experiments can place drivers in crash-imminent conflicts, which will result in a crash without proper driver intervention. Conflicts in the field test can be used for driver data; however, these conflicts tend to be less threatening as they did not end in a crash, thus allowing a driver to respond with less urgency. The V2V research team has conducted controlled driving simulator experiments on two V2V applications, IMA and LTA (Balk, 2013).[5]

2.2.4 Other Research

To supplement current NHTSA and ITS V2V research, data from previous research and literature can be used as inputs into the SIM tool. Previous research can include pre-crash, environmental, driver, or system data. For example, driver reaction times in a rear-end driving conflict can be determined from a previous simulator study conducted by the University of Iowa (Lee et al., 2002). Most data sources and results can be reformed to be used as inputs into the SIM tool.

2.3 General Assumptions

General assumptions are made when implementing the SIM in order to initialize a pre-crash scenario, implement a conflict, and estimate system effectiveness values for crash avoidance systems. The following basic assumptions were made for the Volpe SIM tool:

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[5] Results from this simulator study provided driver performance data for the IMA application that was used as input into the SIM tool to estimate the safety effectiveness of this application.

1. Pre-crash scenario conflicts involve only two vehicles.
2. Host vehicle is a rigid body "light vehicle" (e.g., passenger car, van, or minivan; sport utility vehicle; or light pickup truck with gross vehicle weight rating equal to or under 10,000 pounds).
3. Other vehicle (potential collision partner) is a light vehicle, with similar properties as the host vehicle.
4. Crash avoidance and mitigation are independent of safety system technologies (e.g., video, radar, or communication).[6]
5. Simulated events are ideal and accurate (100% system availability and detection of true conflicts). This assumes no missed, false, or delayed system activations.
6. Event is applicable and ideal for the safety application (no extra vehicles, single conflict).
7. Drivers always respond to a situation with appropriate action (steer and/or brake), as selected prior to running the simulation.[7]
8. All commanded actions apply without interference or delay (e.g., mechanical delays, system failures, etc.).
9. Unintended consequences are not modeled (loss of control, subsequent conflict).
10. Results are generated at the vehicle level (not at the occupant level).

The above assumptions were selected to create a baseline set of assumptions for estimating system effectiveness. Adjustments to the assumptions introduce changes and variables that affect the resulting system effectiveness calculations. These adjustments would require further research and validation, as to the accuracy of the assumption and the resulting impact in the kinematic modules and resulting outputs.

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[6] The simulation does not account for limitations in performance based on technology, but uses results from performance testing to inherit these assumptions. For example, video may not be as effective in darker lighting conditions, inputs for system performance would have to reflect this.

[7] Appropriate actions are pre-defined by the developers in each kinematic module and pre-crash scenario, which represent the most frequent crash avoidance action attempted by the driver in a specific pre-crash scenario, according to GES statistics (Najm et al., 2013).

3   SIM Tool Structure

Figure 3 illustrates the logic and data flow for the Volpe SIM tool that estimates the parameter *PR*. The SIM tool contains kinematic modules (yellow-highlighted squares) that simulate driving conflict scenarios and outcomes. The SIM tool contains independent kinematic modules (e.g., rear-end, SCP, LTAP/OD, lane change, opposite direction/passing maneuver, opposite direction/no maneuver, and rear-end longitudinal queue) which correspond to respective V2V safety applications (i.e., FCW, IMA, LTA, BSW/LCW, DPNW, and EEBL) and their priority pre-crash scenarios (Section 2.1). Kinematic equations are exercised in these modules to recreate the motions and interactions of the HV and RV in driving conflicts matching vehicle movements and critical events of the priority pre-crash scenarios. The SIM tool simulates a driving conflict *with* and *without* the assistance of a crash avoidance application and determines the outcome, "crash" or "no crash," as well as the impact speed and ΔV in case of a crash. Simulation results can then be used to derive system effectiveness in terms of reductions in crashes and injured persons.

3.1   Simulation Modeling

The SIM tool implements Monte Carlo simulation of pre-crash scenarios to determine the effectiveness of crash avoidance applications.[8] Simulations incorporate conflicts determined from information derived from historical crash data and naturalistic driving to configure a pre-crash scenario (e.g., LVS) and initialize a conflict (e.g., travel speed). Once the conflict is initialized, driver-vehicle-system performance data from naturalistic field tests, characterization tests, and other data sources are used to determine the outcomes of conflicts *with* and *without* system assistance. Outputs consist of the number of crashes avoided, resulting impact speeds and *ΔV* values, and standard deviation of the probability of collision. The analyses of these outputs estimate the system effectiveness for crash avoidance applications. System effectiveness values are then applied to Equation **(1)**, the basic benefits equation, to estimate potential safety benefits.

Kinematic modules exercise basic kinematic equations of motion, applying a time-step iterative process.[9] The modules place a light vehicle into a crash-imminent conflict in a pre-crash scenario and progressively move forward in time to simulate the conflict. After initialization of the conflict,[10] the module iterates through the simulation at a time-step increase of 0.1 seconds to determine the outcome. As the time moves forward, the vehicles move and their relative positions, motion (velocity, acceleration), and conflict data (relative range, relative closing speed, time-to-collision (TTC)) are recalculated each time step. The time-step loop continues until the end of the conflict.[11] A conflict is first evaluated without the system. Then the same exact conflict is evaluated with the introduction of a crash avoidance system. Introduction of a crash avoidance system may also introduce new driver behavior (reaction time, braking

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[8] A Monte Carlo simulation is a problem-solving technique that builds models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from the probability functions. Depending on the uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete. Monte Carlo simulation produces distributions of possible outcome values.

[9] Closed form equation modules are in place for select modules to improve processing time for larger simulations. Closed form equations are discussed in subsequent sections.

[10] Simulation begins with time = 0.

[11] A conflict is over when a crash occurs or the position and motion of the vehicles resolve the conflict and make a crash impossible.

force, counter steer level, etc.).[12] The SIM tool allows for this. Each simulation comprises a number of instances, where an instance is a unique driving conflict in the pre-crash scenario. The result of these instances is then analyzed to determine the crash probability, impact speed distributions, and ΔV distributions. The SIM tool is a Monte Carlo simulation that is an aggregate of these instances, or unique conflicts.

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[12] Crash avoidance systems benefit the HV. However, in some conflicts, the RV may beneifit from a warning as well. For example, in a rear-end, the RV may not be able to intervene with a warning, while in an intersection the RV may.
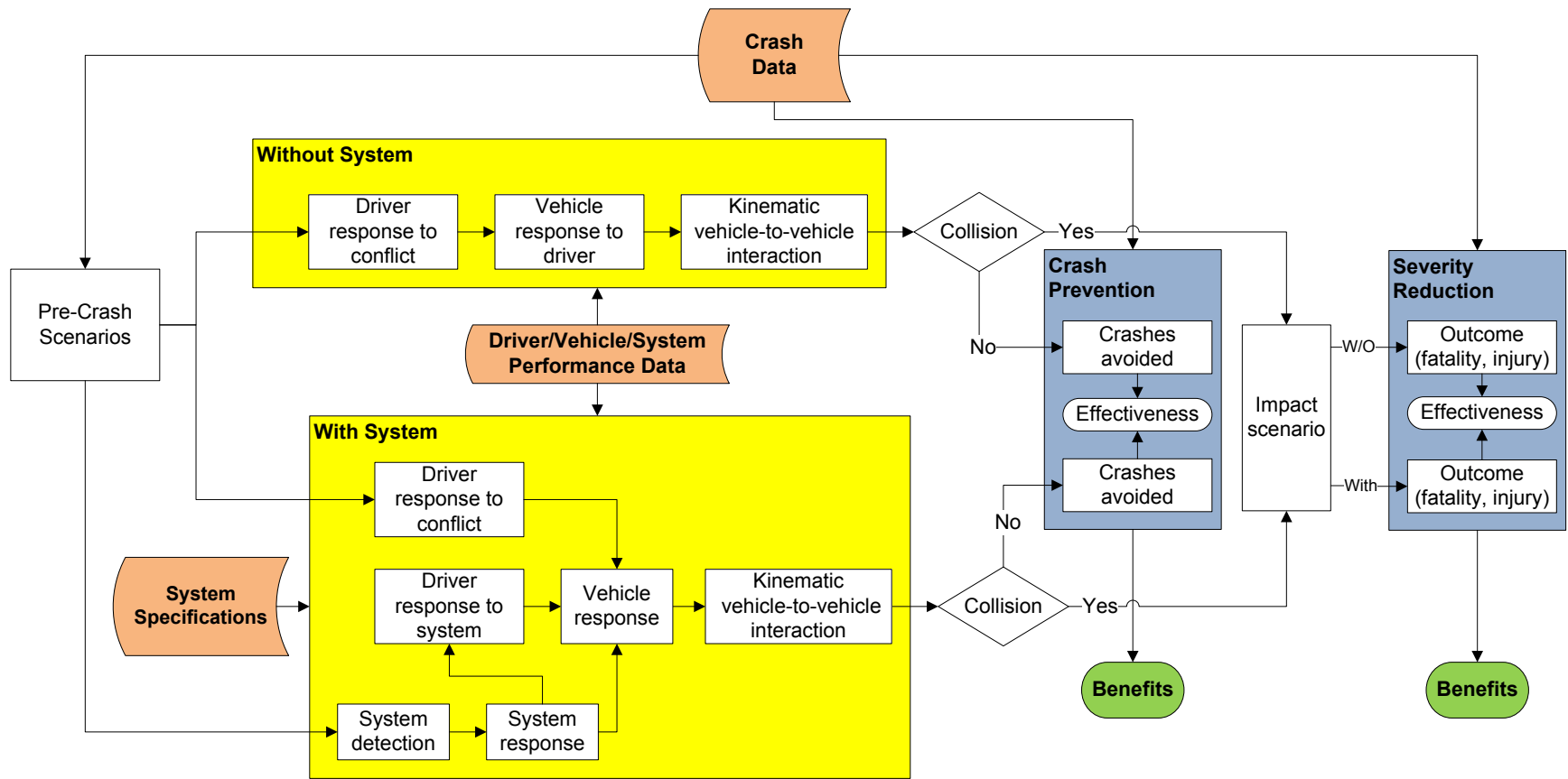
Figure 3. SIM Tool Logic Flow and Structure

3.2   General Kinematic Modeling

Kinematic modules are created individually, but share similar characteristics that include the assumptions listed in Section 2.3 and the following variables:

- Change in acceleration (jerk), j
- Acceleration, a
- Velocity, v
- Distance, d
- Range, R
- Range rate or closing speed, $Rdot$
- Time, t

All kinematic modules are governed by the same basic equations of motion as detailed below:

$$a_{final} = a_{initial} + j \times t \qquad\qquad (4)$$

$$v_{final} = v_{initial} + {}^1\!/_2\, j \times t^2 + a \times t \qquad\qquad (5)$$

$$d_{final} = d_{initial} + {}^1\!/_6\, j \times t^3 + {}^1\!/_2\, a \times t^2 + v \times t \qquad\qquad (6)$$

$$TTC = {}^R\!/_{R_{dot}} \qquad\qquad (7)$$

The modules involve a time-step iterative loop, where the default time step is equal to 0.1 s. At every time step, these governing equations are used to calculate the vehicle motion properties and relative positions. For each instance in the Monte Carlo simulation, values are generated and drawn from the probability distributions, as input into the SIM tool. Once the instance has been initialized, the time-step iterative process begins, using the governing equations, and continues until the end of the instance. The next instance in the simulation would repeat this process until the desired number of instances has been completed. Individual module details are discussed in subsequent sections.

3.3   General Inputs and Outputs

All kinematic modules have similar inputs and outputs. Each kinematic module requires a basic set of inputs to initialize and run the simulation. After the simulation runs, results are tabulated in a general set of outputs.

3.3.1   Inputs

Inputs into the SIM tool include a domain of variables needed to initialize a conflict and determine driver and system responses to the conflict. Once a specific kinematic module and a pre-crash scenario is selected, the user needs to input parameters to both initialize the conflict and proceed through the conflict. All modules require the following parameters:

- Vehicle parameters (length, width, mass, speed, acceleration)
- Driver parameters (response time, response level)
- System parameters (warning time, warning distance, automatic control)

The values of each input variable in the SIM tool are defined by a probability distribution. This probability distribution defines the likelihood a value will be randomly drawn for the applicable variable

and applied to the kinematic equations. Currently, the SIM tool implements the following four probability distributions and their respective parameters (in parentheses):

- Bounded normal distribution (mean, standard deviation, minimum, maximum)
- Bounded log-normal distribution (mean, standard deviation, minimum, maximum)
- Rectangular distribution (minimum, maximum)
- Beta distribution (p, q, minimum, maximum)

When a conflict (an instance within a simulation) is initialized, values are drawn from each of the input distributions and applied, as appropriate, to the kinematic equations, creating the initial conditions for the conflict. Once the conflict has begun, the appropriate drawn values are applied at appropriate times in the conflict to determine the result, both with and without system assistance.

At the conclusion of a conflict and associated treatment conditions (i.e., baseline and treatment, detailed in later sections), new random numbers are drawn and the process is repeated for each instance desired.

3.3.2 Outputs

At the conclusion of a series of conflicts, or instances, and associated treatment conditions, the SIM tool delivers results on the aggregation of all conflicts. Outputs for all modules are identical. The following information is available from SIM results:

- Number of crashes
- Number of non-crashes
- Proportional distribution of impact speeds in 5 km/h incremental bins for crashes occurred
- Proportional distribution of ΔV for the HV in 5 km/h incremental bins for crashes occurred
- Proportional distribution of ΔV for the RV in 5 km/h incremental bins for crashes occurred

The ΔV calculation is a function of vehicle speeds, masses, and impact locations and will be detailed for specific modules in their respective sections.

All output information is provided for the various treatment types (e.g., baseline, with warning, with automatic control) and the various vehicle crash impact modes (e.g., front-back, front-left, front-right, front-front, and side-side). Only impact modes appropriately associated with the pre-crash scenario are presented (e.g., front-back for rear-end conflicts, side-side for lane-change conflicts). Impact modes implement a naming convention in order to indicate which vehicle was the striking vehicle. For the naming convention, the HV's impact location is always indicated first and then followed by the RV's impact location. For example, a "front-back" would indicate the HV's front impacts the RV's back, a rear-end crash. A "left-front" impact mode would indicate the HV's left side was impacted by the RV's front, an intersection-related crash.

The SIM tool also incorporates a function to calculate the standard deviation for the probability of crash estimate at the conclusion of a simulation (Welford, 1962). The probability of crash is determined by dividing the number of collisions by the number of simulation runs. This standard deviation is calculated dynamically after each instance and reported at the end of the simulation. The ordered collection of this standard deviation for all simulation runs is plotted against the number of runs selected for each simulation. The change in the standard deviation as a function of the number of runs tends to decrease exponentially (the change can increase briefly for a small initial number of runs) and asymptotically approach a constant value. The user can then decide, by graphical construction, how many runs they need to reach a desired decrease in the standard deviation for a given simulation.

3.4 Treatment Conditions

To estimate the CPR parameter, the SIM tool simulates conflicts in various conditions (i.e., baseline and treatment). All modules simulate at least two conditions, baseline and Treatment 1, which could represent a warning from a crash avoidance system. Currently, only the rear-end type pre-crash scenarios have the capability to apply automatic control, in the form of braking (Treatment 2 and/or Treatment 3). All condition results are reported individually in the SIM tool.

3.4.1 Baseline

The baseline condition assumes that no warning or automatic control is issued to the HV or RV in the driving conflict. All responses are assumed to be the result of the driver's own recognition of the hazard in the conflict. All modules begin with the baseline condition. Baseline condition variables are user input in the SIM tool, as discussed in Section 3.3.

3.4.2 Treatment 1 – Warning

Treatment 1 creates an identical conflict to the baseline and represents the driver's improved recognition of the conflict from a crash warning system. The warning system is assumed to alter the driver's reaction time and/or response intensity level. Treatment 1 response variables are user input, independent of the response variables in the baseline condition, and need to be input individually. Therefore, the only changes in input data from the baseline to Treatment 1 are driver reaction time and/or driver response level (e.g., braking level/force or counter steer level).

Treatment 1 Variation – Two-Vehicle Implementation (IMA and LTA Only)[13]

In some pre-crash scenarios, it may be beneficial (and possible) to warn only the HV, the RV, or both the HV and the RV. In the case of IMA and LTA applications, the RV may be able to alter its velocity and help to avoid the conflict when the HV alone may not be able to sufficiently avoid the crash.[14] In these instances, a warning is assumed to alter the applicable driver's reaction time and reaction level and therefore change the outcome of the conflict. The SIM tool allows separate reactions times for the HV and RV from an IMA and LTA warning. An improvement in the HV reaction and/or RV reaction may be seen and individually input in the SIM tool.

3.4.3 Treatment 2 – Automatic Control-Stage 1 (Rear-End Pre-Crash Only)

The rear-end crash module can implement automatic braking in the form of system-applied braking or assisted braking. This type of braking is applied at a constant value. Automatic control is applied through two separate methods:

- Driver remains in full control; i.e., once the driver reacts by initiating braking, system-applied braking functions are fully suppressed regardless of braking timing and levels. Driver-initiated braking continues at a constant rate until the end of the conflict.

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[13] This is implemented in conflicts where both vehicles, the HV and RV may react to a warning and avoid a crash, independent of technology.

[14] In intersection crashes, the time window for a potential crash is dependent on the amount of time spent in the potential crash zone by the two vehicles involved. To avoid a crash, the HV may not have to come to a full stop prior to the intersection if the RV is allowed to pass through the intersection prior to the HV entering the intersection.

- Maximum braking is applied when both driver and automatic braking are active simultaneously; the highest braking level between the two is maintained to minimize the stopping distance. This braking level is continued at a constant level until the end of the conflict.

The opportunity to select which method is appropriate is only available upon request. Treatment 2 response variables are user input, independent of previous treatment response variables.

3.4.4   Treatment 3 – Automatic Braking-Stage 2 (Rear-End Pre-Crash Only)

The SIM tool features a two-stage automatic braking capability, where braking intensity from Stage 1 increases to Stage 2 as the crash becomes more imminent. The same two methods from Treatment 2 are available; however, the selected method for Treatment 2 is applied in Treatment 3. The SIM tool will progress to the second stage only after the first stage has already been initiated. Treatment 3 response variables are user input, independent of previous treatment response variables, and need to be input individually.

4 FCW/Rear-End Kinematic Module

The rear-end kinematic module was developed to estimate the effectiveness of the FCW application. An FCW application would sense a rear-end driving conflict, through V2V technology or forward-facing sensor systems, and warn the driver of the HV to take appropriate action to avoid a collision; however, some instances may allow for and/or apply automatic braking. Table 1 lists the domain of variables needed for the rear-end module in the SIM tool.

Table 1. Rear-End Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	TTC Warning	s	Numeric	Statistical distribution
	Host Initial Velocity	km/h	Numeric	Statistical distribution
	Lead Initial Velocity	km/h	Numeric	Statistical distribution
	Lead Braking Force at Alert	g	Numeric	Statistical distribution
HOST Braking	Host Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Braking Force in **Control**	g	Numeric	Statistical distribution
	Host Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Braking Force in *Treatment*	g	Numeric	Statistical distribution
HOST Steering	Host Steering Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Steering Jerk in **Control**	g/s	Numeric	Statistical distribution
	Host Steering Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Steering Jerk in *Treatment*	g/s	Numeric	Statistical distribution
HOST Automatic Braking	Host Stage 1 Autobrake TTC Activation	s	Numeric	Statistical distribution
	Host Stage 1 Autobraking Force	g	Numeric	Statistical distribution
	Host Stage 2 Autobrake TTC Activation	s	Numeric	Statistical distribution
	Host Stage 2 Autobraking Force	g	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

The rear-end module is capable of evaluating incremental system effectiveness when automatic control is introduced into a crash avoidance system using the designed treatment conditions. Simulations are run individually through the baseline and treatment conditions, and results can be compared to determine estimates of effectiveness.[15] The SIM tool allows for the implementation of two-staged automatic braking. Detailed information is described in Section 3.4.

Rear-end conflicts are further classified into three separate pre-crash scenarios, defined by the RV motion: stopped (LVS), moving at slower constant speed (LVM), and decelerating (LVD). In addition, in each pre-crash scenario, there are three potential avoidance maneuvers that the HV can perform (e.g., braking, steering, or braking and steering). Each of these pre-scenarios and avoidance maneuvers can be described by a set of unique kinematic equations.

4.1 Lead Vehicle Stopped

LVS is described by an HV traveling at constant speed, approaching a stopped RV ahead in the same lane. The HV is encountering a driving conflict and is on a collision course with the RV unless the HV responds with an appropriate avoidance maneuver. A crash in an LVS conflict can be avoided through

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[15] When treatment conditions are run, the initial conflict setup is identical to the initial conflict in the baseline run. This is true for each distinct run in the Monte Carlo simulation.

HV driver braking and/or steering. The initial conditions of the LVS conflict are characterized by the HV initial longitudinal velocity, v_{HVLon}, and the RV's initial longitudinal velocity, equal to 0 in the LVS. In the LVS conflict, the RV initial velocity, v_{RV}, is set to zero and continues to be stopped as the HV approaches. Methodology detailing the initialization of the conflict and accompanying avoidance maneuvers is detailed in the sections below.

4.1.1 Host Braking

A common response to an LVS conflict is to apply the brakes and attempt to stop prior to any collision. A detailed breakdown and analysis of the governing kinematic equations from Section 3.2 are given below. The SIM kinematic modules deploy a time-step iterative process in lieu of closed-form equations.[16] For this module, a key metric is the closing speed of the HV. The closing speed is defined as the difference between the HV velocity and RV velocity, R_{dot}, as seen in Equation (8). However, with a braking-only avoidance maneuver, the closing speed is labeled as the longitudinal direction only, R_{dotLon}.

$$R_{dot}(t) = |\vec{v}_{HV}(t) - \vec{v}_{RV}(t)| \qquad (8)$$
$$R_{dotLon}(t) = v_{HVLon}(t) - v_{RV}(t) \qquad (9)$$

To initialize the conflict, the HV is placed directly behind the stopped RV based on the inputs for the time-to-collision threshold of the warning/trigger, $TTC(0)$, and closing speed, R_{dotLon}. Together, these two variables determine the trigger point for the conflict. A trigger point can be defined as the start of a conflict, at a given warning time, or relative time before the potential crash. The initial range, $R_{initial}$, between the front of the HV and the rear of the RV, is determined by solving for R in Equation (7) when $t = 0$:

$$R_{initial} = R_{dotLon}(0) \times TTC(0) \qquad (10)$$

The HV initially approaches the stopped RV at a constant speed, then the driver reacts by releasing the accelerator and pressing on the brakes. During the HV driver reaction time from the trigger point to braking initiation, denoted as tR, the HV travels distance d_{HVLon} at constant speed:

$$d_{HVLon} = v_{HVLon} \times tR \qquad (11)$$

$R_{initial}$ is reduced by distance d_{HVLon}, to the resulting range at brake, $R_{@brake}$ from the front of the HV to the rear of the RV.

$$R_{@Brake} = R_{initial} - d_{HVLon} \qquad (12)$$

At $R_{@brake}$, the HV brakes at a constant deceleration level, a_{HVLon}, until the HV is able to come to a complete stop or collides with the RV. The stopping distance of the HV, d_S, is calculated by:

$$d_s = \frac{v_{HVLon}^2}{-2 \times a_{HVLon}} \qquad (13)$$

Figure 4, below, shows key parameters used in defining and exercising the LVS conflict with a braking response.

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[16] Closed-form equations may be used in certain modules to reduce processing time. Closed-form equations offer infinite resolution, but limit flexibility. Details of specific closed-form implementation are detailed later in the report.
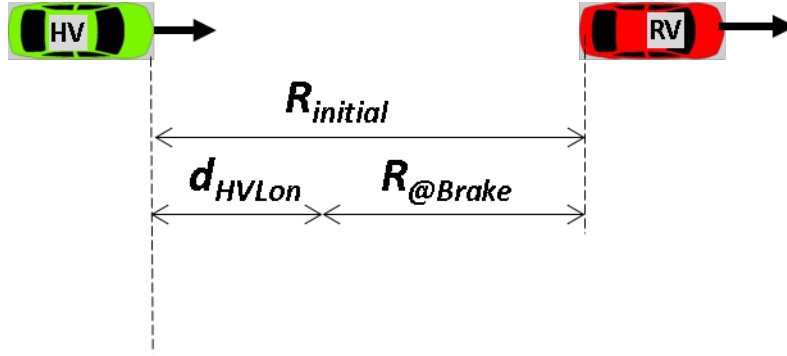
Figure 4. Diagram of the LVS Conflict and Parameters

The HV avoids an LVS crash if $d_S < R_{@brake}$. Otherwise, a crash may occur at impact speed, R_{dotLon}, (where $R_{dotLon} \equiv v_{HVLon}$) in an LVS conflict, from Equation **(9)** at the time of the crash. A crash is defined when the HV and RV occupy the same space and one vehicle has a speed greater than zero. This would conclude one conflict, or one trial, in the SIM tool simulation.

4.1.2 Host Steering

Crash data suggests that drivers attempt to perform additional avoidance maneuvers to avoid an LVS conflict, including steering. Steering may be performed independent of braking. The HV encounters the RV and responds with a steering response with the steering mode modeled by a lateral jerk.

The conflict is defined identically to the braking maneuver, by the HV initial longitudinal velocity and the RV initial velocity.

In the steering maneuver, R_{dot} is determined implicitly by the SIM code: the relative speed between the HV and the RV given by Equation **(8)** above. To initialize the conflict, the HV is placed directly behind the stopped RV based on the inputs for $TTC(0)$, and closing speed, R_{dotLon}. For steering, TTC is redefined as $TTEL$, the time at which the HV and RV would have equal longitudinal coordinates. These two variables together determine the trigger point for the conflict. The trigger point is defined as the start of a conflict: a given warning time or relative time before the HV and RV would have equal longitudinal coordinates. The initial range, $R_{initial}$, between the front of the HV and the rear of the RV is given by Equation **(14)**.

$$R_{initial} = R_{dotLon}(0) \times TTEL(0) \qquad (14)$$

The HV approaches the stopped RV longitudinally at a constant speed, v_{HVLon}. The HV travels distance, d_{HVLon} from its initial point, at its constant longitudinal velocity prior to any HV driver reaction time. As the HV approaches the RV, the HV reacts by turning to the left[17] at time $tRSteer$. The HV turns at a constant jerk magnitude, j, until the end of the simulation.

The tool calculates the longitudinal range between the HV and the RV, using the longitudinal relative positions, $R_{Lon}(t)$, with $d_{RV} = R_{initial}$, until a crash occurs at impact speed, R_{dot}, or the conflict is resolved. Equations are based on the governing equations from Section 3.2 and can be found in **Appendix B**. The tool also calculates the lateral range, R_{Lat}, between the HV right side (taking into account the rotation of

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[17] Left was selected as an initial maneuver; however, the two vehicles are aligned along the center with no offset. Results would be identical if the coding was adjusted to move to the right.

the HV) and the RV left side. A crash occurs if at any point $R_{Lon}(t) \leq 0$. The conflict is resolved if $R_{Lon}(t) > 0$ and $R_{dotLon}(t) \leq 0$ are true, or if $R_{Lat}(t) > 0$ is true. This would conclude one conflict or one trial in the SIM tool simulation.
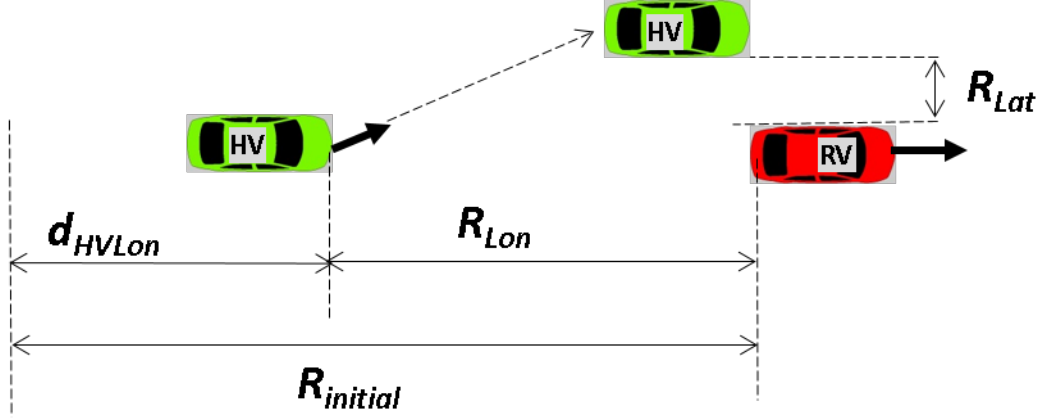
Figure 5. Diagram of the LVS Conflict and Parameters with Steering Avoidance

4.1.3 Host Braking and Steering

The LVS conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction times and reaction level inputs are required. During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that, because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as they have been described in the previous sections.

4.1.4 Treatment

In Treatment 1 (warning condition), the SIM tool assumes benefit would come from an improved driver reaction time and/or an improved driver reaction level (harder braking and/or steering), in the same exact conflict as the baseline condition. An improvement in driver reaction time would allow for a shorter distance traveled during the reaction time; an improvement in the reaction force would lead to a decrease in stopping distance or decrease in distance needed to steer away from the lead vehicle.

When automatic braking is applicable, as designed in Treatments 2 and 3, the SIM tool will initiate the staged system braking in the same exact conflicts as the baseline and warning conditions, with activation criteria defined by TTC parameters. For Treatment 2, the first stage will be activated when the TTC for Activation of Stage 1 automatic braking criterion, TTC_{AB1}, is met. The SIM tool calculates TTC at every iterative time step (every 0.1 s). When the first stage of automatic braking is activated, the system braking begins at the deceleration level of stage 1 automatic braking, a_{AB1}, and the HV will decelerate at a constant rate. For Treatment 3, where a second stage of automatic braking is applicable, the HV will decelerate at the deceleration level of stage 2 automatic braking, a_{AB2}, when the TTC for activation of stage 2, TTC_{AB2}, is met. Logic models described in Section 3.4 apply. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

4.2   Lead Vehicle Moving at Slower Constant Speed

LVM is described by an HV traveling at constant speed, approaching a slower RV traveling at constant speed ahead in the same lane. The HV is encountering a driving conflict and is on a crash course with the RV unless the HV responds with an appropriate avoidance maneuver. The LVM conflict is similar to the LVS conflict, with the only variation being the constant speed of the RV. The LVM conflict is characterized by the closing speed, R_{dotLon}, as defined by Equation **(9)**. This assumes that the RV is always traveling at a slower constant speed, creating a potential conflict.

4.2.1   Host Braking

The LVM conflict is initialized similarly to the LVS. The HV is placed directly behind the RV, at distance, $R_{initial}$ *(≡ $d_{RV}(0)$; initial relative starting point for RV)* from Equation (10) based on the inputs for time-to-collision threshold of the warning/trigger, $TTC(t)$, and closing speed, R_{dotLon}, calculated when t = 0. The HV and RV travel distances, d_{HVLon} and d_{RV}, respectively, from their initial points, at their respective constant velocities prior to any HV driver brake reaction time, tR. Distances traveled, d_{HVLon} and d_{RV}, are calculated. As the HV approaches the RV, the HV reacts by releasing the accelerator and pressing on the brakes at time tR. At the onset of the brake pedal, the HV brakes at a constant deceleration level, a_{HVLon}, until the end of the simulation. The RV continues to move at constant speed. The velocity and distance traveled by the HV decreases, accounting for HV braking, a_{HVLon}. The tool continues to calculate the longitudinal range between the HV and the RV, using their relative positions, until a crash occurs or the conflict is resolved. A crash occurs if at any point $R_{Lon}(t) \leq 0$. The conflict is resolved if $R_{Lon}(t) \geq 0$ and $R_{dotLon}(t) \leq 0$ are true. This would conclude one conflict, or one trial, in the SIM tool simulation.

4.2.2   Host Steering

Similar to the LVS, this conflict allows for alternate avoidance maneuvers, allowing for a steering response. The HV is placed directly behind the RV, at distance, $R_{initial} \equiv d_{RV}(0)$; initial relative starting point for RV from Equation **(14)**, based on the inputs for $TTEL(0)$, and closing speed, R_{dot}, calculated when t = 0. The HV and RV travel distances, d_{HVLon} and d_{RV} respectively from their initial points, at their respective constant velocities prior to any HV driver reaction time. Distances traveled, d_{HVLon} and d_{RV}, are calculated as the HV approaches the RV; the HV then reacts by turning to the left at time $tRSteer$, until the end of the simulation.

The tool calculates the longitudinal range, R_{Lon}, between the HV and the RV until a crash occurs or the conflict is resolved. The tool also calculates the lateral range, R_{Lat}, between the HV right side (taking into account the rotation of the HV) and the RV left side. A crash occurs if at any point $R_{Lon}(t) \leq 0$. The conflict is resolved if $R_{Lon}(t) > 0$ and $R_{dotLon}(t) \leq 0$ are true, or if $R_{Lat}(t) > 0$ is true. This would conclude one conflict, or one trial, in the SIM tool simulation.

4.2.3   Host Braking and Steering

The LVM conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction times and reaction level inputs are required. During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Due to this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as described in the previous sections.

4.2.4   Treatment

Similar to LVS, system effectiveness for the LVM conflict is derived from an improvement in driver reaction time and/or driver reaction level. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

4.3   Lead Vehicle Decelerating

LVD is described by an HV traveling at constant speed and approaching an RV traveling at a slower constant speed and decelerating at a constant level. It is assumed that the RV is already in the state of braking at the start of the conflict and continues at a constant level until the RV comes to a complete stop or the conflict ends. The HV is encountering a driving conflict and is on a crash course with the RV unless the HV responds with an appropriate avoidance maneuver. The LVD conflict is similar to the other rear-end conflicts; however, the RV has a slower velocity preceding constant braking. The LVD is characterized by the closing speed, R_{dotLon}, as defined by Equation (9). The range rate R_{dotLon}, must be positive for the SIM tool to create an LVD conflict. Based on Equations (9) and (10), if $v_{RV} \geq v_{HVLon}$ then $R_{initial} \leq 0$ and the SIM tool cannot initialize the conflict. Additional inputs would be needed to define the conflict, such as a headway variable, and are not accounted for in the SIM tool.

4.3.1   Host Braking

The LVD conflict is initialized similarly to the previous rear-end conflicts. The HV is placed directly behind the RV at distance $R_{initial}$ ($\equiv d_{RV}(0)$; initial relative starting point for RV$_)$, based on the inputs for time-to-collision of the warning/trigger, $TTC(t)$, vehicle speeds (v_{HVLon} and v_{RV}) and the lead vehicle braking level a_{RV}, when t = 0. The HV and RV travel distances, d_{HVLon} and d_{RV}, respectively, prior to any HV driver braking reaction time, tR. The HV travels at constant initial velocity, v_{HVLon}, while the RV has a constant average deceleration level, a_{RV}, applied to its initial velocity, v_{RV}.

The formulation of $TTC(t)$ in the LVD with HV braking conflict is more complex than in the LVS and LVM braking conflicts, in order to account for the deceleration of the lead vehicle. Since a collision could occur while the lead vehicle is still decelerating or after the lead vehicle has fully stopped, TTC is calculated as a piecewise function that accounts for both possibilities. Likewise, the initial range is calculated as a piecewise function of the user-input initial TTC, $TTC(0)$.

If the lead vehicle would be stopped before the collision occurred, R_{Init_S} is used, which is simply the total distance the HV will travel, minus the stopping distance of the RV. With no intervention, this guarantees that the vehicles will collide exactly at time $TTC(0)$.

$$R_{Init\_S} = TTC(0) \times v_{HVLon} - \frac{v_{RV}(0)^2}{-2a_{RV}}, \qquad (15)$$

If the collision would occur while the lead vehicle is still decelerating, R_{Init_D} is used, which is derived by isolating the constant term (the initial range) from the quadratic motion equation.

$$R_{Init\_D} = \frac{1}{2}a_{RV}TTC(0)^2 + (v_{HVLon} - v_{RV})TTC(0) \qquad (16)$$

The criterion for choosing which range equation to use is a simple check on whether the total time required for the RV to reach zero velocity is less than the specified $TTC(0)$:

$$R(0) = \begin{cases} R_{Init\_S}, & if \ \frac{v_{RV}}{-a_{RV}} \leq TTC(0) \\ R_{Init\_D}, & Otherwise \end{cases}$$

The equations below calculate the updated TTC at any time during the simulation. In the case where the lead vehicle would be stopped before impact, the TTC is simply the total distance from the HV's current position to the RV's stopping point, divided by the current velocity of the HV:

$$TTC_{Stopped}(t) = \frac{R_{Lon}(t) + \frac{v_{RV}(0)^2}{-2a_{RV}}}{v_{HVLon}} \tag{17}$$

If the impact would occur while the lead vehicle is still decelerating, TTC is simply the positive solution of the quadratic expression for the distance between the two vehicles:

$$TTC_{Decel}(t) = \frac{-R_{dotLon}(t) + \sqrt{R_{dotLon}(t)^2 - 2a_{RV}R_{Lon}(t)}}{-a_{RV}} \tag{18}$$

To determine which expression is appropriate, $TTC_{Decel}(t)$ must be calculated. If $TTC_{Decel}(t) \times (-a_{RV}) \geq v_{RV}(t)$ is true, the lead vehicle would have fully stopped before impact, so instead $TTC_{Stopped}$ is used:

$$TTC(t) = \begin{cases} TTC_{Stopped}(t), & if \ TTC_{Decel}(t) \times (-a_{RV}) \geq v_{RV}(t) \\ TTC_{Decel}(t), & Otherwise \end{cases}$$

As the HV approaches the RV, the HV driver reacts by releasing the accelerator and pressing on the brakes at time *tR*. At the onset of the brake pedal, the HV brakes at constant deceleration level, a_{HVLon}, until the end of the simulation. The RV continues to brake at constant deceleration until it comes to a complete stop (after which it remains stopped) or the simulation ends. The velocity and distance traveled by the HV are modified to account for a_{HVLon}. The tool continues to calculate the longitudinal range between the front of the HV and the RV until a crash occurs or the conflict is resolved. A crash occurs if at any point $R_{Lon}(t) \leq 0$. The conflict is resolved if $R_{Lon}(t) > 0$ and $R_{dotLon}(t) \leq 0$ are true. This would conclude one conflict, or one trial, in the SIM tool simulation.

4.3.2 Host Steering

Similar to the previous LVS and LVM conflicts, this conflict allows for alternate avoidance maneuvers, allowing for a steering response. The HV is placed directly behind the RV at distance $R_{initial}$ ($\equiv d_{RV}(0)$; initial relative starting point for RV), based on the inputs for *TTEL(0)*, vehicle speeds (v_{HVLon} and v_{RV}) and the lead vehicle braking level a_{RV}, when $t = 0$. For the steering modes, TTC is again redefined as *TTEL*, the time at which the HV and RV would have equal longitudinal coordinates. The HV and RV travel distances, d_{HVLon} and d_{RV}, respectively, prior to any HV driver reaction. Distances traveled are calculated assuming the HV has a constant initial velocity, v_{HVLon}, and the RV has a constant average deceleration level, a_{RV}, applied to its initial velocity, v_{RV}.

If the lead vehicle would be stopped before the vehicles will have equal longitudinal coordinates, R_{Init_S} is used for the initial separation. With no intervention, this guarantees that the vehicles will have equal longitudinal coordinates at time *TTEL(0)*.

$$R_{Init\_S} = TTEL(0) \times v_{HVLon} - \frac{v_{RV}(0)^2}{-2a_{RV}}, \qquad (19)$$

But if the vehicles would have equal longitudinal coordinates while the lead vehicle is still decelerating, R_{Init_D} is used.

$$R_{Init\_D} = \frac{1}{2} a_{RV} TTEL(0)^2 + (v_{HVLon} - v_{RV}) TTEL(0) \qquad (20)$$

The criterion for choosing which range equation to use is a simple check on whether the total time required for the remote vehicle to reach zero longitudinal velocity is less than the specified *TTEL(0)*:

$$R_{initial} = \begin{cases} R_{Init\_S}, & if \ \dfrac{v_{RV}(0)}{-a_{RV}} \leq TTEL(0) \\ R_{Init\_D}, & Otherwise \end{cases}$$

$R_{initial}$ is then used for the steering modes as the initial longitudinal distance separating the RV and the HV. The times *TTC(t)* are not generally known because the steering motion can resolve the conflict.

As the HV approaches the RV, the HV reacts by turning to the left at time *tRSteer*. At the onset of the turn, the HV turns at a constant jerk magnitude, *j*, until the end of the simulation. The RV continues to brake at constant deceleration until it comes to a complete stop (after which it remains stopped) or the simulation ends. The tool continues to calculate the longitudinal and lateral ranges between the HV and the RV until a crash occurs or the conflict is resolved. A crash occurs if at any point $R_{Lon}(t) \leq 0$. The conflict is resolved if $R_{Lon}(t) > 0$ and $R_{dotLon}(t) \leq 0$ are true, or if $R_{Lat}(t) > 0$ is true. This would conclude one conflict, or one trial, in the SIM tool simulation.

4.3.3 Host Braking and Steering

The LVD conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction times and reaction level inputs are required. During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as they have been described in the previous sections.

4.3.4 Treatment

Similar to LVS and LVM, system effectiveness for LVD conflicts are derived from an improvement in driver reaction time and/or driver reaction level. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

Figure 6 illustrates a generalized flowchart for the rear-end kinematic module.

Input (GUI)
$v_{HVLon}(0)$ = Host Velocity
tR = Host Braking Reaction Time
a_{HV} = Host Braking
tRSteer = Host Steering Reaction Time
J = Host Steering Jerk Level
$v_{RV}(0)$ = Remote Velocity
a_{RV} = Remote Braking
TTC(0) = Time-to-Collision@Trigger

■ *User inputs values for t = 0 and t = tR*
■ *Some variables change as a function of time*

Random Number Generation

Initialization @t=0
$$R_{dot} = v_{HVLon} - v_{RV}$$
$$R_{Initial} = R_{dotLon} \times TTC$$

Time Step
ts = 0.1

CONFLICT START
t = 0.1
If Lead Vehicle Stopped (LVS)
$v_{RV} = 0$
$a_{RV} = 0$
If Lead Vehicle Moving (LVM)
$a_{RV} = 0$

t ≤ tR OR t ≤ tRSteer

No — Yes

Motion Loop
If t > tR then HV Brake
If t > tRSteer then HV Steer
RV Constant Motion

Motion Loop
HV Constant Motion
RV Constant Motion

Conflict Status
Define R
Define R_{dotLon}
Define TTC
Define TTEL

Return to Motion Loop

$R \le 0$ OR $R_{Lat} \le 0$

Yes — No

Crash Results
Impact Speed = R_{dot}
ΔV_{HV}
ΔV_{RV}

■ *SIM tool outputs 3 values after a crash (impact speed and ΔV for HV and ΔV for RV*

Next Time Step
$$t = t + ts$$

Figure 6. Generalized Flowchart for the Rear-End Conflict Simulation

24

4.4   Delta V Calculation

As described earlier, part of the output from the SIM tool is a distribution of ΔV values. Within the SIM tool, ΔV is automatically calculated based on the resulting impact speed and vehicle masses. Equations (21) and (22) below describe the method for determining ΔV. These equations assume 1) an ideal inelastic collision, which accounts for conservation of momentum, and 2) that the centers of masses collide without rotation. Below, ΔV_{HV}, is the ΔV experienced by an HV with mass m_{HV} when involved in a collision with an RV with mass m_{RV}. The ratio of the masses is termed, δ.

$$\delta_{HV} = \frac{m_{HV}+m_{RV}}{m_{RV}} \qquad \text{and} \qquad \delta_{RV} = \frac{m_{HV}+m_{RV}}{m_{HV}} \tag{21}$$

$$\Delta V_{HV} = {R_{dot}}/{\delta_H} \qquad \text{and} \qquad \Delta V_{RV} = {R_{dot}}/{\delta_R} \tag{22}$$

The adjustments to calculate ΔV_{RV} are also shown above. At the end of each trial, if a crash occurs, a ΔV is calculated. When all trials are completed, separate distributions of ΔV values in 5 km/h incremental bins are independently produced for the HV and the RV. The distributions define the frequency at which an HV would experience a certain ΔV under the submitted conditions; the same is true for the RV distribution. Each value is defined as the percentage of the given crashes that had a vehicle that experienced a ΔV in the respective bin.

5 IMA/Crossing Path Kinematic Module

The crossing path module was developed to estimate the effectiveness of the IMA application. An IMA application would sense a potential conflict where two vehicles are about to cross paths at a road junction, initially traveling from perpendicular directions, and warn the HV driver of the host vehicle. An IMA application would be implemented through V2V technology. The current module assumes that the paths of the HV and RV intersect, thus resulting in a perpendicular crash angle (90 degrees) and both vehicles reaching the potential crash zone (intersection overlap of their paths) at the same time. Changing the angle of approach between the vehicles (intersection angle) would alter the shape and size of the potential conflict area; however, the kinematics surrounding another approach angle would be very similar.[18] The simulation assumes both vehicles travel straight through the intersection, leading to an SCP conflict as illustrated in Figure 7.
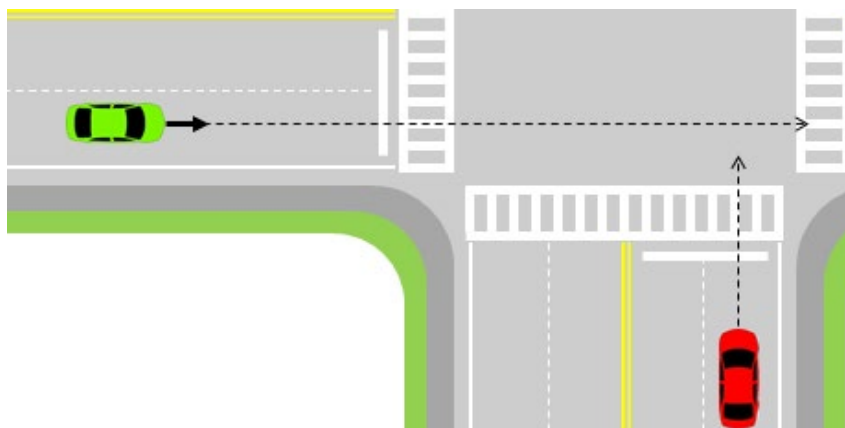
Figure 7. Schematic for a Straight Crossing Path (SCP) Conflict

SCP conflicts are further classified by the HV motion and the RV direction.[19] The HV may approach the intersection at constant speed or be stopped at the intersection and attempt to accelerate through the intersection. When the HV approaches at constant speed, it is termed an *SCP-Moving* (SCP-M) conflict. When the HV is stopped and later accelerates through the intersection, it is termed an *SCP-Stopped* (SCP-S) conflict. Additionally, the RV can enter the intersection from the HV's left or right side, giving variation to the SCP-M or SCP-S conflict.

In an SCP-M conflict, both the RV and HV travel at constant speed and are on a crash course in the intersection if no evasive action is taken by the HV to alter the outcome (assuming no RV action/response). In an SCP-S conflict, the RV travels at constant speed while the HV has a constant acceleration from stop through the intersection. The HV is placed at a pre-defined distance away from the intersecting zone. The SCP-S conflict does not guarantee a collision between the two vehicles. This will be discussed in the SCP-S section. In both conflicts, different evasive actions can be taken by either the HV (i.e., braking and/or accelerating) and/or the RV (i.e., braking).

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[18] Currently, the SIM tool uses 90-degree intersections. Using an iterative time-step calculation, changing the intersection angle would not alter vehicle approach dynamics, but would change the probability of crash potential. Altering the intersection angle significantly may alter the classification of this pre-crash scenario.

[19] In variations of SCP implementation, it is feasible that a warning could be issued to either vehicle approaching the intersection; for this reason, either vehicle could be designated as an HV or RV, or both vehicles could be HVs as noted in Section 3.4.

5.1   Straight Crossing Paths – Moving

The SCP-M conflict is typically caused by a driver violating the traffic control device or the right of way at a road junction. The violation may be intentional by the driver or may happen due to a driver recognition error of what is ahead at the junction. Table 2 shows the domain of variables needed for a simulation of the SCP-M conflict in the SIM tool.

Table 2. SCP-M Domain of Variables for Input into the SIM tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Remote Vehicle Entering From		Multiple Choice	Direction relative to HV
	Vehicle(s) with Application		Multiple Choice	Drivers with improved reaction
	Time to Intersecting Paths	s	Numeric	Statistical distribution
	Host Initial Velocity	km/h	Numeric	Statistical distribution
	Remote Initial Velocity	km/h	Numeric	Statistical distribution
HOST Braking	Host Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Braking Force in **Control**	g	Numeric	Statistical distribution
	Host Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Braking Force in *Treatment*	g	Numeric	Statistical distribution
HOST Accelerating	Host Acceleration Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Acceleration Force in **Control**	g	Numeric	Statistical distribution
	Host Acceleration Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Acceleration Force in *Treatment*	g	Numeric	Statistical distribution
REMOTE Braking	Remote Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Remote Braking Force in **Control**	g	Numeric	Statistical distribution
	Remote Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Remote Braking Force in *Treatment*	g	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

The SCP-M conflict is defined by the time-to-intersecting paths, *TTI*. The conflict is initialized such that both the HV and the RV reach the edge of the crash zone at the same time, to ensure a crash, unless a vehicle responds with an appropriate evasive maneuver. The crash zone is the area in which a crash could occur, and is defined by the width of the two vehicles. Figure 8 illustrates the location and size of the potential crash zone.
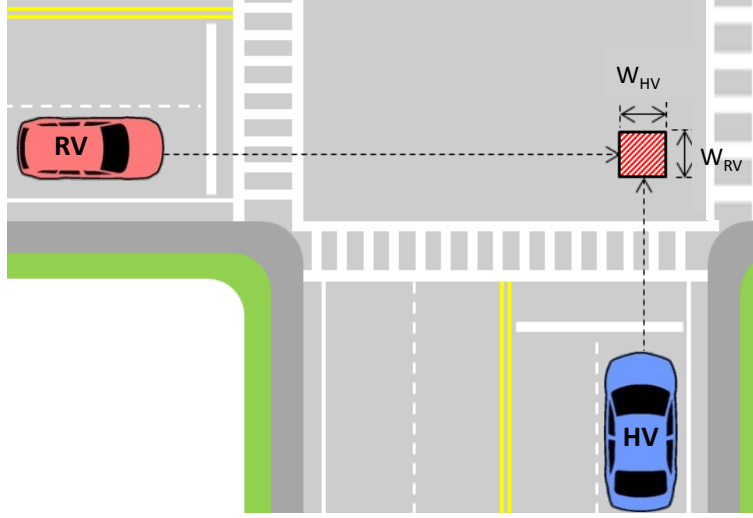
Figure 8. Definition of Potential Crash Zone in an SCP Conflict

5.1.1 Host Braking

The HV is located at a distance back from the crash zone based on the initial *TTI* and the HV initial velocity, v_{HV}. Equation (10) can be modified to account for *TTI* and initial HV velocity, v_{HV}, in place of *TTC* and R_{dot}, respectively, to determine the initial range when t = 0; in this case, the HV's initial range until reaching the crash zone, R_{HV}. In a similar manner, the RV is located at a distance back from the crash zone, initial range R_{RV}, which is calculated from the initial *TTI* and RV initial velocity, v_{RV}, when t = 0.

$$R_{HV} = v_{HV}(t) \times TTI(t) \quad \text{and} \quad R_{RV} = v_{RV}(t) \times TTI(t) \quad (23)$$

The RV is placed so that its path is perpendicular to that of the HV's path, as shown in Figure 9. The direction of the RV, relative to the HV, is determined from user input. Kinematic solutions in the SIM tool are independent of the RV's direction; however, the RV's direction dictates the impact modes for crashes.
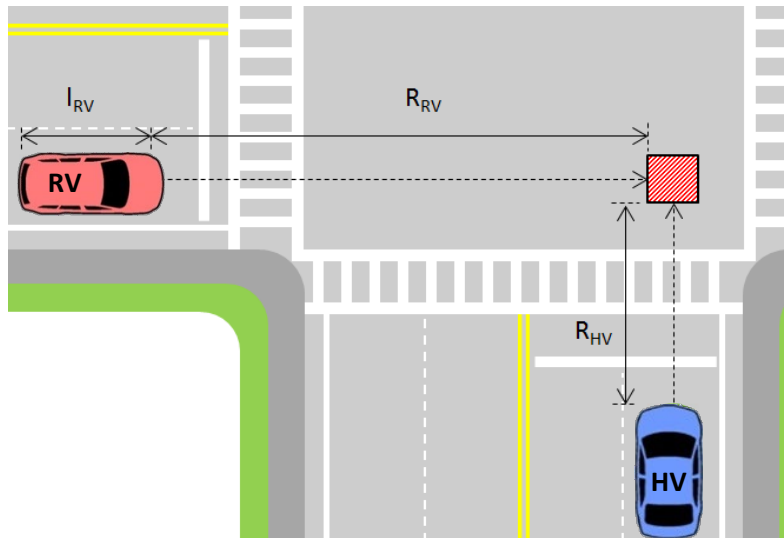
Figure 9. Initialization and Identification of Parameters for the SCP-M Simulation

The two vehicles approach the intersection on their respective paths. For this example, it is assumed that only the HV reacts, while the RV remains at constant speed (the SIM tool allows for the HV and RV to react to the conflict independent of one another). The RV reaches the crash zone at the defined *TTI*. To clear the crash zone at *TTCZ$_{RV}$*, the RV must cross the initial range, *R$_{RV}$,* and an additional distance, which is the sum of the width of the HV and the length of the RV, *w$_{HV}$* and *l$_{RV}$*, respectively. The parameter *TTCZ$_{RV}$* is calculated according to Equation.

$$TTCZ_{RV} = \frac{R_{RV} + w_{HV} + l_{RV}}{v_{RV}} \tag{24}$$

The conflict begins with the HV moving at constant speed *v$_{HV}$*. After the appropriate reaction time *tR* has elapsed, the driver applies the brakes. The distance from the front of the HV to the edge of the crash zone at the onset of braking is defined as *R$_{@brake}$*. At this point in time and beyond, *tR*, the HV brakes at constant deceleration *a$_{HV}$*. The time it takes the HV to reach the crash zone, *TTRZ$_{HV}$*, is determined by the quadratic equation below:

`If tR < TTI`

$$R_{@Brake} = R_{HV} - v_{HV} \times tR \tag{25}$$

$$TTRZ_{HV} = \frac{v_{HV} - \sqrt{v_{HV}{}^2 + 4 \times 0.5 \times a_{HV} \times R_{@Brake}}}{-2 \times 0.5 \times a_{HV}} + tR \tag{26}$$

Assuming *tR < TTI,* the RV will reach the crash zone first while it remains at constant speed. A crash can occur if *TTRZ$_{HV}$ ≤ TTCZ$_{RV}$* and *TTCZ$_{HV}$ ≥ TTRZ$_{RV}$*. If a crash occurs, the impact speed is defined as the speed of the vehicle suffering frontal impact. This would conclude one conflict, or trial, in a treatment condition.

5.1.2   Host Accelerating

An alternate avoidance maneuver would be for the HV to accelerate and attempt to clear the crash zone prior to the RV reaching the crash zone. If accelerating, the time it takes the HV to reach the crash zone, *TTRZ$_{HV}$,* is determined by the quadratic equation below:

`If tR < TTI`

$$R_{@Accel} = R_{HV} - v_{HV} \times tR \tag{27}$$

$$TTRZ_{HV} = \frac{-v_{HV} + \sqrt{v_{HV}{}^2 + 4 \times 0.5 \times a_{HV} \times R_{@Brake}}}{2 \times 0.5 \times a_{HV}} + tR \tag{28}$$

The equations for HV decelerating and accelerating are very similar, to differentiate between acceleration and deceleration using the same variable, *a$_{HV}$*, deceleration is represented by a negative *a$_{HV}$*, while acceleration is represented using a positive *a$_{HV}$*.

5.1.3   Remote Braking

In this kinematic module, it is possible for the RV to be provided with an attempted avoidance maneuver. The RV may attempt to brake, using the same kinematic equations as described above. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level. .

5.1.4   Treatment

The SCP-M conflict allows the user to specify whether the warning system is present in the HV, RV, or both. Depending on the availability of the warning, the HV and/or RV may have varying reaction times and levels between control and treatment. If the warning is not present, the vehicle would see no change in reaction time or level. Similar to the rear-end module, the IMA effectiveness results from an improved reaction time and/or braking/acceleration level by the responding vehicles. Varying which vehicle has an improved reaction time or braking/acceleration level can alter the impact mode, as described in Section 3.3, and then the subsequent ΔV value. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

5.2   Straight Crossing Paths – Stopped

The SCP-S conflict is described by an HV stopped at an intersection with an RV at constant speed approaching the same intersection from a perpendicular direction. The HV releases the brake and accelerates into the intersection attempting to cross. While either vehicle is still in the crash zone, the partner vehicle reaches the crash zone and a crash occurs. Table 3 shows the domain of variables needed for the simulation of the SCP-S conflict in the SIM tool.

Table 3. SCP-S Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Remote Vehicle Entering From		Multiple Choice	Direction relative to HV
	Vehicle(s) with Application		Multiple Choice	Drivers with improved reaction
	Time to Intersecting Paths	s	Numeric	Statistical distribution
	Host Initial Distance	m	Numeric	Statistical distribution
	Host Initial Acceleration	g	Numeric	Statistical distribution
	Remote Initial Velocity	km/h	Numeric	Statistical distribution
HOST Braking	Host Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Braking Force in **Control**	g	Numeric	Statistical distribution
	Host Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Braking Force in *Treatment*	g	Numeric	Statistical distribution
HOST Accelerating	Host Acceleration Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Acceleration Force in **Control**	g	Numeric	Statistical distribution
	Host Acceleration Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Acceleration Force in *Treatment*	g	Numeric	Statistical distribution
REMOTE Braking	Remote Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Remote Braking Force in **Control**	g	Numeric	Statistical distribution
	Remote Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Remote Braking Force in *Treatment*	g	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

5.2.1 *Host Braking*

Similar equations from the SCP-M conflict apply to the RV in this conflict, as the RV motion is identical in both conflicts. The RV is located at a distance R_{RV} back from the crash zone, based on the initial *TTI* and the RV initial velocity, v_{RV}, from Equation (23). The HV's front is placed at a user-specified initial distance R_{HV} to the crash zone (labeled *Host Initial Distance* in Table 3). The HV then accelerates at a constant acceleration level, a_{HV}, from an initial low speed, $v_{HV}(0)$. It is assumed that the HV accelerates immediately from the start of the event and continues to accelerate at a constant level until the driver reacts, at time *tR*, by releasing the accelerator pedal and pressing the brake pedal. The distance traveled by the HV during the acceleration period, $d_{HV}(tR)$, is:

$$d_{HV}(tR) = 0.5 \times a_{HV}(0) \times tR^2 + v_{HV}(0) \times tR \qquad (29)$$

The HV reaches the following speed right before braking, $v_{HV}(tR)$ at the end of *tR*:

$$v_{HV}(tR) = a_{HV}(0) \times tR + v_{HV}(0) \qquad (30)$$

The stopping distance, d_s, of the HV in response to braking at deceleration level $a_{HV}(tR)$ is computed by:

$$d_s = \frac{v_{HV}^2(tR)}{-2 \times a_{HV}(tR)} \qquad (31)$$

With HV braking, a crash can be avoided if $(d_{HV}(tR) + d_S) < R_{HV.}$

Figure 10 presents a general flowchart for the simulation of the SCP-M and SCP-S conflicts. The major difference between the two conflicts is that in SCP-S, HV initial distance and initial acceleration are user input, along with a pre-defined initial low speed (set to 0). The use of these variables means that the HV's position can no longer be defined as a function of *TTI*, since it may be impossible to reconcile a given *TTI* value with the user inputs. The SCP-S conflict cannot guarantee that a collision will occur between the HV and RV for any given set of inputs. The SIM tool will only guarantee that their (projected) paths do intersect.

5.2.2 Host Accelerating

Similar to the SCP-M conflict, an alternate avoidance maneuver is for the HV to accelerate through the crash zone (in addition to the HV initial acceleration). For the HV accelerating case a passing distance, d_p, is computed by Equation (32) (where a_{HV} is now positive and $t > tR$). For this case, a crash cannot necessarily be avoided if $(d_{HV}(tR) + d_p) < R_{HV}$ since the vehicle would not be stopped.

$$d_p = \frac{1}{2} a_{HV}(tR)(t - tR)^2 + v_{HV}(tR)(t - tR) \qquad (32)$$

5.2.3 Remote Braking

In this kinematic module, it is possible for the RV to be provided with an attempted avoidance maneuver. The RV may attempt to brake, and the same kinematic equations as described in the SCP-M conflict are used. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level.

5.2.4 Treatment

As mentioned earlier, this simulation does not guarantee a crash even with no avoidance maneuver, and for certain input parameters, it may be impossible for both the HV and RV to occupy the crash zone at the same time at any point in the simulation. Further, the set of input parameters may allow for the HV to fully leave the intersection prior to the RV reaching the crash zone.

Identical to the SCP-M conflict, the SCP-S conflict allows the user to select which vehicles will receive warnings. Assuming an improved reaction time and/or braking/acceleration level, any observed IMA effectiveness will be reflected in the number of crashes that occur and their resulting impact speeds, and *ΔV* distributions. Any change in impact mode will be reflected appropriately in the results, and in impact speed and *ΔV* calculations. At the completion of all instances in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3. Figure 10 illustrates a generalized flowchart for the SCP kinematic module.

5.3 Delta V Calculation and Impact Modes

Similar to the rear-end module, outputs for the SCP module include distributions of impact speeds and *ΔV* values by impact mode.

However, unlike the rear-end module, the SCP module has the potential for multiple impact modes. A rear-end crash is confined to the front of an HV striking the back of an RV (front-back). An SCP conflict depends on the initial direction of the RV relative to the HV (from left, from right) and which vehicle enters the potential crash zone first. Because of this, four possible impact modes are possible, using the convention from Section 3.3: front-right, left-front, front-left, and right-front. Based on the impact mode and impact speed, *ΔV* is calculated for both vehicles involved.

$\mathit{\Delta V}$ is calculated similarly to the rear-end module, using Equations (21) and (22). However, the impact speed is considered to be the velocity of the striking vehicle (the vehicle with the frontal impact), rather than R_{dot}. For example, in a "front-right" impact, the HV is listed with the frontal impact. In Equation (22), the R_{dot} term would be replaced with the velocity of the HV, v_{HV}, at the time of impact. If the impact mode were to be listed as "left-front", the R_{dot} term would be replaced with the velocity of the RV, v_{RV}, at the time of impact (the RV had the frontal impact). In both examples, Equation (21) would remain the same for the HV and RV. Again, this calculation assumes an ideal, inelastic, center-of-mass collision.[20]

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[20] Changes in this assumption would introduce potential rotation and changes in motion after impact. These changes introduce variations in ΔV calculations that may differ from empirical data.

Input (GUI)
TTI = Time-to-Intersection@Trigger
d$_{HV}$ = Host Initial Distance
a$_{HV}$ = Host Initial Acceleration
v$_{HV}$ = Host Initial Velocity
v$_{RV}$ = Remote Initial Velocity
atR$_{HV}$ = Host Acceleration Reaction Time
atR$_{HV}$ = Host Acceleration Level
atR(b)$_{HV}$ = Host Braking Level
atR(b)$_{HV}$ = Host Braking Reaction Time
tR$_{RV}$ = Remote Reaction Time
atR(b)$_{RV}$ = Remote Braking Level

▪ *User inputs values for t = 0 and t = tR*
▪ *Some variables change as a function of time*

Random Number Generation

Initialization
@t=0
If SCP-M
$R = v \times TTI$
If SCP-S
Use d$_{HV}$

Time Step
ts = 0.1

CONFLICT START
t = 0.1

t ≤ atR(b)
OR
t ≤ atR

No   Yes

Motion Loop
If t > tR(b)$_{HV}$ then HV Brake
If t > tR(b)$_{RV}$ then RV Brake
If t > tR$_{HV}$ then HV Accelerate

Motion Loop
HV Constant Motion
RV Constant Motion

Return to Motion Loop

Conflict Status
Define R$_{HV}$
Define R$_{RV}$
Define TTI

Counter Update
$t = t + ts$

No

Crash Detection

▪ *Internal sub-routine to determine if the vehicles overlap*

Crash Results
Impact Speed = v(t+ts) of Frontal Impact
ΔV$_{HV}$
ΔV$_{RV}$

Yes

▪ *SIM tool outputs 3 values after a crash (impact speed and ΔV for HV and ΔV for RV*
▪ *Impact speed is determined as the speed of the vehicle with the frontal impact at the time of the crash*

Figure 10. Flowchart of SCP Conflict Situation

6 LTA/Left Turn Across Path/Opposite Direction Kinematic Module

The LTAP/OD kinematic module was developed to estimate the effectiveness of the LTA application. An LTA application would sense and warn the driver of a conflict where two vehicles approach a junction from opposite directions. As the two vehicles approach, the RV attempts to continue to cross straight and the HV attempts to turn left across the path of the RV. This pre-crash scenario is referred to as the LTAP/OD, as illustrated in Figure 11.
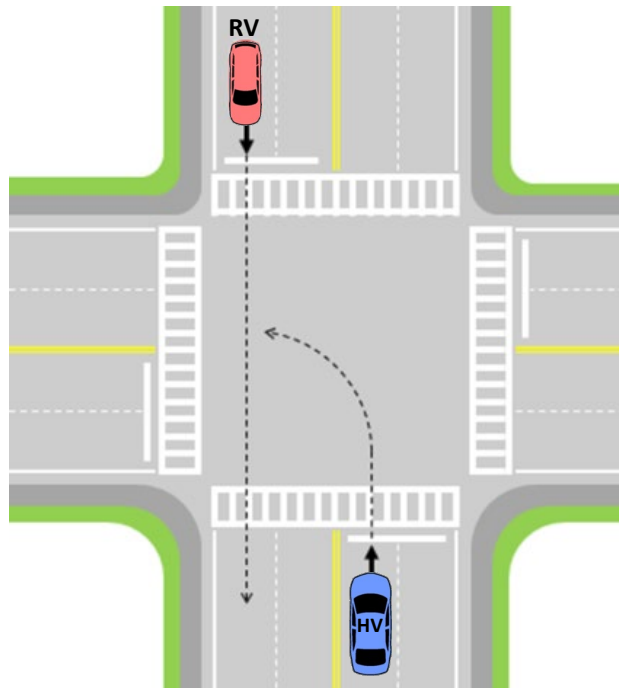
Figure 11. Schematic for the LTAP/OD Pre-Crash Scenario

LTAP/OD conflicts are further classified by the HV motion: when the HV approaches the intersection at constant speed and attempts to turn left, it is termed an *LTAP/OD-Moving* (LTAP/OD-M) conflict, and when the HV is stopped and later accelerates through the intersection to turn left, it is termed an *LTAP/OD-Stopped* (LTAP/OD-S) conflict.

6.1 LTAP/OD – Stopped

Similar to the SCP-S conflict, the LTAP/OD-S conflict does not guarantee a collision between the two vehicles (further explained in detail after the kinematic analysis). [21] The LTAP/OD-S conflict is described by an HV stopped at an intersection waiting to turn left. An RV moving at constant speed is approaching the same intersection from the opposite direction and is intending to travel straight through. The HV initiates the left turn, accelerates, and enters the intersection. As the HV attempts the left turn, the RV enters the intersection and collides with the HV. Table 4 lists the domain of variables needed for the LTAP/OD-S simulation in the SIM tool.

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[21] SCP-S and LTAP/OD-S conflicts are the only driving conflicts in which a crash is not guaranteed if no countermeasure action is taken by the HV.

Table 4. Table of LTAP/OD Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Vehicle(s) with Application		Multiple Choice	Drivers with improved reaction
	Time to Intersecting Paths	s	Numeric	Statistical distribution
	Turn Radius	m	Numeric	Statistical distribution
	Host Initial Velocity	km/h	Numeric	Statistical distribution
	Host Initial Acceleration	g	Numeric	Statistical distribution
	Remote Initial Velocity	km/h	Numeric	Statistical distribution
HOST Braking	Host Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Braking Force in **Control**	g	Numeric	Statistical distribution
	Host Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Braking Force in *Treatment*	g	Numeric	Statistical distribution
HOST Accelerating	Host Acceleration Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Acceleration Force in **Control**	g	Numeric	Statistical distribution
	Host Acceleration Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Acceleration Force in *Treatment*	g	Numeric	Statistical distribution
REMOTE Braking	Remote Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Remote Braking Force in **Control**	g	Numeric	Statistical distribution
	Remote Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Remote Braking Force in *Treatment*	g	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

The LTAP/OD-S conflict is very similar to an SCP-S conflict in that distances to the crash zone for the HV and RV are used to define the conflict. These distances are functions of turn radius, velocity, and time to intersection. The crash zone is defined as the location in the intersection where the potential crash could occur; this is where the paths of the two vehicles would intersect. Figure 12 illustrates the location and size of the potential crash zone in an LTAP/OD conflict.
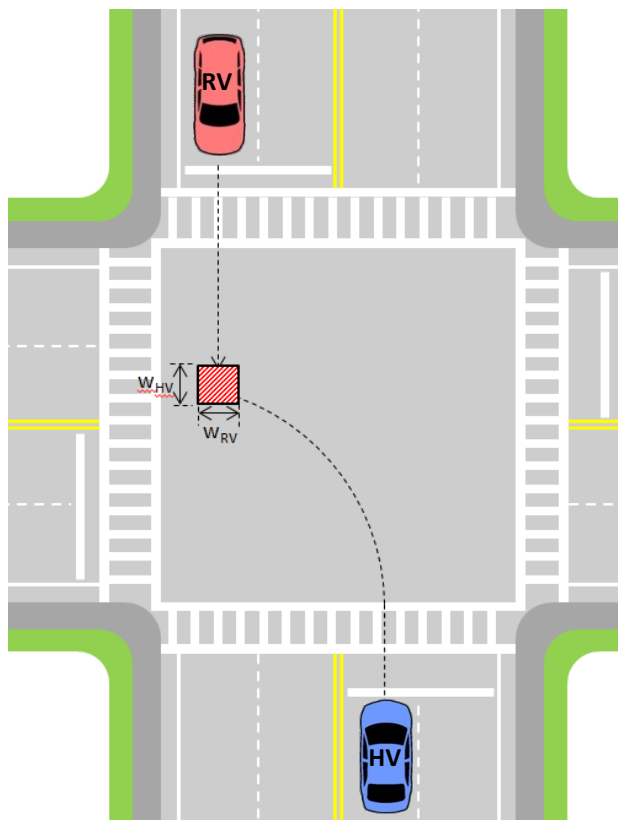
Figure 12. Definition of Potential Crash Zone in an LTAP/OD Conflict

The location of the potential crash zone is at the end of the HV's left turn. As its rear bumper is exiting the crash zone, the HV is completing the full left turn that is equivalent to one quarter of a circle. It is assumed that the HV returns to a straight trajectory instantly after completing the turn and exiting the crash zone, with the HV motion becoming perpendicular to the RV motion. Figure 13 shows the relative location of this crash zone. Since the 90-degree turn is not complete until the HV exits the crash zone, the crash zone is not exactly rectangular, with the leading and trailing edges being somewhat curved to match the turn radius. The rectangular shape in Figure 12 and Figure 13 is simplified for illustrative purposes only.
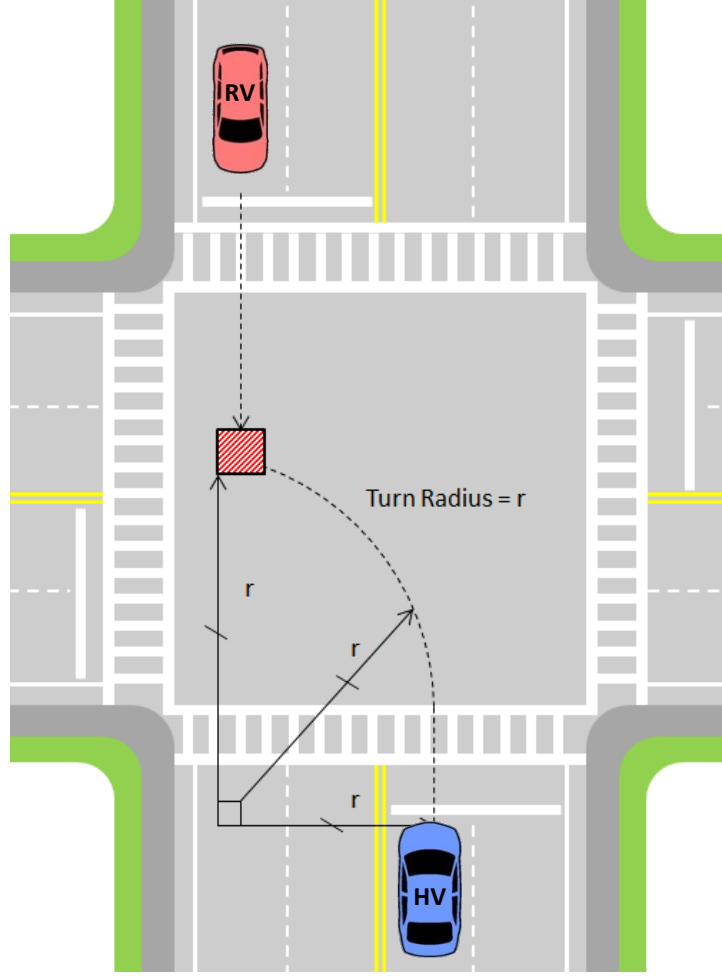
Figure 13. Relative Location of Crash Zone in an LTAP/OD Conflict (Not to Scale)

6.1.1 Host Braking

Generally, the equations governing the LTAP/OD-S conflict are similar to the SCP-S conflict. The HV exits the crash zone after completing a quarter of a circle turn. The default radius for this turn in the SIM tool is 7.5 meters (adjustable). The range for the HV to clear the crash zone, $RCCZ_{HV}$, is a function of the turn radius, r, and the length of the HV, l_{HV}:

$$RCCZ_{HV} = \frac{2\pi \times r}{4} + l_{HV} \qquad (33)$$

LTAP/OD-S kinematic equations are very similar to those used in the SCP module. The RV is located at a distance, R_{RV}, back from the crash zone, based on *TTI* and the RV initial velocity, v_{RV}. Figure 14 shows these parameters.

Figure 14. Additional Parameters that Define the LTAP/OD-S Conflict and Kinematics

The HV accelerates at a constant acceleration level, a_{HV}, from an initial low speed, v_{HV}. The same assumptions from the SCP-S apply (instant and constant acceleration from the start of the event). The HV continues to accelerate at a constant level, until the time of driver reaction, tR, when the driver releases the accelerator pedal and presses the brake pedal. The distance traveled by the HV during the initial acceleration period, $d_{HV}(tR)$, is determined by Equation (29). The range remaining for the HV to clear the crash zone at the time of braking/accelerating, $R_{@Brake}$, is determined by:

$$R_{@Brake} = RCCZ_{HV} - d_{HV}(tR) \tag{34}$$

The HV reaches a maximum speed, $v_{HV}(tR)$, during an initial acceleration period prior to attempting any avoidance maneuver at tR, as determined from Equation (30). As the HV begins to brake, the stopping distance, d_s, can be determined from Equation (31). If the HV is braking and $d_s < (R_{@Brake} - l_{HV})$, then the HV will not enter the crash zone and a crash is avoided. However, the HV may also exit the crash zone prior to the RV entering. The total time (from event start) needed for the HV to clear the crash zone is defined as (where $a_{HV}(tR)$ is negative):

$$TTCZ_{HV} = \frac{v_{HV}(\text{tR}) - \sqrt{v_{HV}(tR)^2 + 4 \times 0.5 a_{HV}(tR) \times R_{@Brake}}}{-2 \times 0.5 a_{HV}(tR)} + tR \tag{35}$$

Figure 15 illustrates the flowchart of the LTAP/OD-S simulation in the SIM tool. If $TTCZ_{HV} < TTI$, then the HV exits the crash zone prior to the RV entering and a crash is avoided. Additionally, the RV may

exit the crash zone prior to the HV entering the crash zone, $TTRZ_{HV} > TTCZ_{RV}$, and the crash may be avoided. As mentioned, the left turn motion slightly alters the shape of the crash zone. This report specifies the closed-form equations that describe a rectangular approximation of this shape; however, the SIM tool's use of iterative kinematic motion, two-dimensional vehicle modeling, and crash detection, easily accounts for this contortion of the crash zone.

6.1.2 Host Accelerating

The LTAP/OD-S conflict allows for an alternate avoidance maneuver for the HV – the HV may accelerate (beyond initial acceleration) to try and avoid the crash. The same logic used for Host Braking applies to the case of additional acceleration, except the total time needed for the HV to clear the crash zone is defined as (where $a_{HV}(tR)$ is now positive):

$$TTCZ_{HV} = \frac{-v_{HV}(\text{tR}) + \sqrt{v_{HV}(tR)^2 + 4 \times 0.5 a_{HV}(tR) \times R_{@Brake}}}{2 \times 0.5 a_{HV}(tR)} + tR \qquad (36)$$

6.1.3 Remote Braking

In this kinematic module, it is possible for the RV to be provided with an attempted avoidance maneuver. The RV may attempt to brake, and the same kinematic equations as described in the SCP-M conflict can be used. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level.

6.1.4 Treatment

As mentioned earlier, this simulation does not guarantee a crash, and given the set of input parameters, it may not be possible for both the HV and RV to occupy the crash zone at the same time at any point in the simulation. The given set of HV inputs (distance, velocity, acceleration, *TTI*) may not allow for a physically possible situation, and therefore only the RV is dependent on *TTI*. If an LTAP/OD-S crash occurs, the impact speed is retained and incorporated in the results.

The LTAP/OD module allows the user to select which vehicle(s) will receive warnings. Assuming an improved reaction time and/or braking/acceleration level due to the warning, any effectiveness seen will be reflected in the presence of crashes, resultant impact speeds, and *ΔV* distributions. Any change in impact mode will be reflected appropriately in the results, impact speed, and *ΔV* calculations. At the completion of trials in all treatment conditions, the SIM tool outputs results, as detailed in Section 3.3.

6.2 LTAP/OD – Moving

The LTAP/OD-M conflict is described by an HV moving at constant speed before entering the intersection. An RV is approaching the same intersection at constant speed from the opposite direction, intending to travel straight through. The HV initiates a left turn and enters the intersection across the path of the RV, creating a driving conflict with the RV. The domain of variables needed for the LTAP/OD-M simulation in the SIM tool are those needed for the LTAP/OD module shown in Table 4.

The LTAP/OD-M conflict is very similar to an SCP-M conflict, where distances to the crash zone for the HV and RV are used to define the conflict. The crash zone is defined similarly to the LTAP/OD-S conflict and as described in Figure 12.

6.2.1 Host Braking

Generally, the equations governing the LTAP/OD-M conflict are similar to the SCP-M conflict. The HV exits the crash zone after completing a quarter of a circle turn.[22] The range for the HV to clear the crash zone, RCCZ_{HV}, is a function of the turn radius, r, and the length of the HV, l_{HV}, and is given by Equation (33).

The RV is located at a distance, R_{RV}, back from the crash zone, based on *TTI* and the RV initial velocity, v_{RV}.
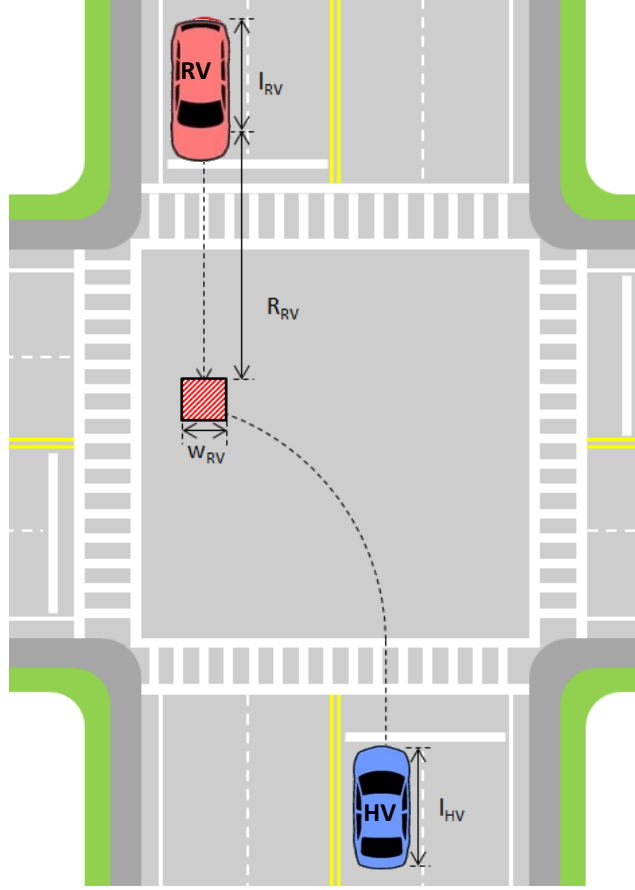
The HV continues to move at the constant velocity, $v_{HV}(0)$, until the time of driver reaction, tR, when the driver presses the brake pedal. The distance traveled by the HV during this time period, $d_{HV}(tR)$, is determined by Equation (29) with $a_{HV}(0) = 0$. The range remaining for the HV to clear the crash zone at the time of braking, $R_{@Brake}$, is determined by Equation (34).

As the HV begins to brake, the stopping distance, d_s, can be determined from Equation (31). If $d_s <$ ($R_{@Brake}$ - l_{HV}), then the HV will not enter the crash zone and a crash is avoided. The HV may also exit the crash zone prior to the RV entering. The total time (from event start) needed for the HV to clear the crash zone is defined as Equation (35) from the LTAP/OD-S conflict.

6.2.2 Host Accelerating

The LTAP/OD-M conflict allows for an alternate avoidance maneuver for the HV, where the HV may accelerate (beyond initial acceleration) to try and avoid the crash. The same logic used for Host Braking, described above, applies to the case of additional acceleration, except the total time needed for the HV to clear the crash zone is defined with acceleration, as opposed to deceleration (where $a_{HV}(tR)$ is now positive).

6.2.3 Remote Braking

In this kinematic module, it is possible for the RV to be provided with an attempted avoidance maneuver. The RV may attempt to brake, and the same kinematic equations as described in the SCP-M conflict can be used. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level.

6.2.4 Treatment

The LTAP/OD module allows the user to select which vehicle(s) will receive warnings. Assuming an improved reaction time and/or braking/acceleration level due to the warning, any effectiveness seen will be reflected in the presence of crashes, resultant impact speeds, and *ΔV* distributions. Any change in impact mode will be reflected appropriately in the results, impact speed, and *ΔV* calculations. At the completion of trials in all treatment conditions, the SIM tool outputs results, as detailed in Section 3.3. Figure 11 shows the generalized flowchart for the LTAP/OD kinematic module.

6.3 Delta V Calculation and Impact Modes

Similar to the previous modules, the LTAP/OD module generates distributions of impact speeds and *ΔV* values by impact mode. Like the SCP module, the potential for multiple impact modes exists. The

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[22] The default radius for this turn in the SIM tool is 7.5 meters (adjustable).

LTAP/OD module is capable of three impact modes: front-left, right-front, and front-front. All impact modes use the same naming convention detailed in Section 3.3. Based on the impact mode and impact speed, ΔV is calculated for both vehicles involved.

ΔV is calculated in the same manner as for the SCP module (Section 5.3), using Equations (21) and (22). The impact speed is considered to be the velocity of the striking vehicle, which is the vehicle with the frontal impact mode. However, in the instance of the "front-front" impact mode, the range rate, R_{dot}, is defined by the closing speed (as opposed to the impact speed of the vehicle with the frontal impact, as both vehicles have a frontal impact). The value R_{dot} is calculated similar to Equation (9); however, the vehicles are considered to be travelling in opposite directions. This modifies the equation to Equation (37), where t = time at impact:

$$R_{dot}(t) = v_{HV}(t) + v_{RV}(t) \qquad (37)$$

In Equation (37), the velocities are both positive. Again, Equations (21) and (22) would apply using the appropriate R_{dot} term in the appropriate impact mode. This calculation assumes an ideal, inelastic, center-of-mass collision.

6.4   Determining Impact Modes

Since the HV is rotating (i.e., it follows a curved path), its orientation can be determined by using a rotation matrix. This orientation, plus the HV's center position, gives the HV's overall front-right position. The RV's front-left position is also calculated. The x-component and y-component distances between these two positions are then known. These two distances are divided by their respective velocities (in the case of the y-component velocity, the closing speed is used) to give times that determine which vehicle enters the potential crash zone first. If the HV's heading is between 270 and 315 degrees, then the vehicle entering more recently is the striking vehicle and suffers frontal impact. If the HV's heading is between 315 and 360 degrees, then both vehicles suffer frontal impact.

Input (GUI)
TTI = Time-to-Intersection@Trigger
r = radius of HV turn
v$_{HV}$ = Host Initial Velocity
a$_{HV}$ = Host Initial Acceleration
v$_{RV}$ = Remote Initial Velocity
tR(b)$_{HV}$ = Host Braking Reaction Time
atR(b)$_{HV}$ = Host Braking Level
tR(a)$_{HV}$ = Host Acceleration Reaction Time
atR(a)$_{HV}$ = Host Acceleration Level
tR(b)$_{RV}$ = Remote Reaction Time
atR(b)$_{RV}$ = Remote Braking Level

■ *User inputs values for t = 0 and t = tR*
■ *Some variables change as a function of time*

Random
Number
Generation

Initialization
@t=0
$$R_{HV}(t) = \frac{2\pi \times r}{4}$$
$$R_{RV}(t) = v_{RV} \times TTI(t)$$

Time Step
ts = 0.1

CONFLICT START
t = 0.1

t ≤ tR(b)
OR
t ≤ tR(a)

No   Yes

Motion Loop
If t > tR(b)$_{HV}$ then HV Brake
If t > tR(b)$_{RV}$ then RV Brake
If t > tR(a)$_{HV}$ then HV Accelerate

Motion Loop
HV Constant Motion
RV Constant Motion

Return to Motion Loop

Conflict Status
Define R$_{HV}$
Define R$_{RV}$
Define TTI

Next Time Step
$$t = t + ts$$

No

Crash Results
Impact Speed = *f*(impact mode)
ΔV$_{HV}$
ΔV$_{RV}$

■ *SIM tool outputs 3 values after a crash (impact speed and ΔV for HV and ΔV for RV*
■ *Impact speed is a function of impact mode*

Yes

Crash
Detection

■ *Internal sub-routine to determine if the vehicles overlap*

Figure 15. Flowchart of LTAP/OD Conflict Simulation

43

7 BSW/LCW/Lane Change Kinematic Module

The lane change (LC) kinematic module was developed to estimate the safety effectiveness of the BSW/LCW application that would sense a conflict where two vehicles are traveling in the same direction on the same road in adjacent lanes and the HV attempts to make a lane change. It is assumed that the RV (or at least a substantial portion) is in the collision area of the lane adjacent to the HV. A potential collision area is defined as the area in the adjacent lane to the left or right of the HV, as defined by Figure 16.
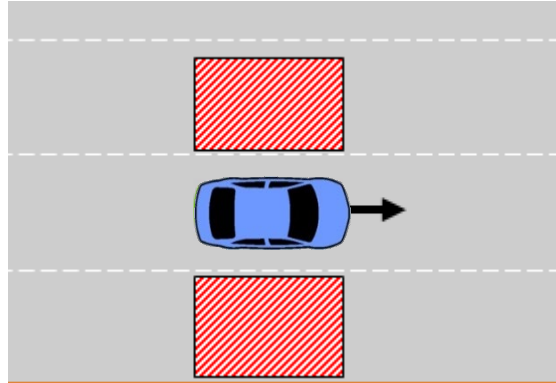
Figure 16. Definition of Potential Collision Area for Lane Change Conflict, with Respect to the HV

It is also assumed that the longitudinal speeds of the HV and RV are relatively close and the difference is negligible. This allows the RV to remain in the collision zone for the duration of the event. The event begins when the HV initiates the lane change with lateral motion determined by the user; this is a lane change/maneuver (LC/Man) conflict. The HV continues the lane change, increasing its lateral speed and decreasing its lateral distance to the RV. The HV's trajectory will lead to a collision if there is no response from the HV or RV.

In a lane change conflict, the HV may attempt to avoid a collision by braking, steering, accelerating, or braking and steering; the primary response is for the HV to steer back into the original travel lane, using a counter steer. In its current state, the SIM tool only allows the RV to attempt to avoid this collision by using braking and/or steering only if the HV is steering.[23]

7.1 Lane Change/Maneuver Conflict

The LC/Man conflict begins when the HV is fully committed to a lane change and the maneuver has just been initiated or was already in progress.[24] The conflict also assumes that motion is continuous, the RV is in the conflict zone, and the longitudinal speed difference between the RV and HV is negligible.[25] These assumptions effectively reduce the LC module to a one-dimensional conflict, similar to the rear-end conflict (LVS). The only difference is the inclusion of lateral jerk, the rate of change in lateral acceleration, in the motion equations. More information on this can be found in **Appendix C**.

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[23] The RV response is only modeled when the HV is steering, as steering is the primary response for the HV. Limitations in development have led to limiting variations for RV avoidance.

[24] A fully commited lane change implies that the driver is intent and active in changing lanes, with some lateral motion and will continue to do so.

[25] Secondary impacts caused from rotation are not modeled.

Table 5 shows the domain of variables needed for the simulation of the LC/Man conflict in the SIM tool.

Table 5. LC/Man Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Host Distance to Lane Marker at Alert	m	Numeric	Statistical distribution
	Remote Distance to Lane Marker at Alert	m	Numeric	Statistical distribution
	Host Initial Velocity [Longitudinal] at Alert	km/h	Numeric	Statistical distribution
	Host Initial Velocity [Lateral] at Alert	m/s	Numeric	Statistical distribution
	Host Acceleration [Lateral] at Alert	g	Numeric	Statistical distribution
	Host Steering Jerk at Alert	g/s	Numeric	Statistical distribution
HOST Braking	Host Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Braking Force in **Control**	g	Numeric	Statistical distribution
	Host Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Braking Force *Treatment*	g	Numeric	Statistical distribution
HOST Steering	Host Counter Steering Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Counter Steering Jerk in **Control**	g/s	Numeric	Statistical distribution
	Host Counter Steering Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Counter Steering Jerk in *Treatment*	g/s	Numeric	Statistical distribution
HOST Accelerating	Host Acceleration [Longitudinal] Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Acceleration [Longitudinal] Force in **Control**	g	Numeric	Statistical distribution
	Host Acceleration [Longitudinal] Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Acceleration [Longitudinal] Force in *Treatment*	g	Numeric	Statistical distribution
REMOTE Braking	Remote Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Remote Braking Force in **Control**	g	Numeric	Statistical distribution
	Remote Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Remote Braking Force in *Treatment*	g	Numeric	Statistical distribution
REMOTE Steering	Remote Counter Steering Reaction Time in **Control**	s	Numeric	Statistical distribution
	Remote Counter Steering Counter Jerk in **Control**	g/s	Numeric	Statistical distribution
	Remote Counter Steering Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Remote Counter Steering Counter Jerk in *Treatment*	g/s	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

The LC/Man conflict begins as the HV is placed an initial lateral distance away from the RV, $R_{initial}$. The value $R_{initial}$ is obtained by adding the user-specified RV initial distance to lane marker, R_{RVLat}, and the HV initial distance to lane marker, R_{HVLat}.

$$R_{initial} = R_{HVLat} + R_{RVLat} \qquad (38)$$

The 'distance to lane marker' parameter is selected since this measure is easily observed from naturalistic driving field operational tests. The obtained values of this measure from field tests for an HV can then be applied to an RV, if RV data is not obtainable. Figure 17 illustrates these parameters.
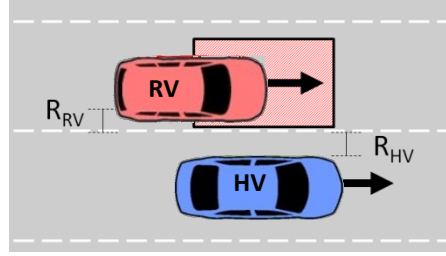
Figure 17. Distance Parameters for LC/Man Pre-Crash Scenario

7.1.1 Host Steering

The conflict begins with the HV initiating the lane change or already in the process of changing lanes. This is determined by the input of HV lateral speed at alert (v_{HVLat}), HV lateral acceleration at alert (a_{HVLat}), and HV lateral jerk at alert (j). During the lane change maneuver, the lateral acceleration increases at constant rate (jerk), increasing the lateral speed, and decreasing the lateral range to the RV. A lateral acceleration limit of 0.4 g is enforced.

The HV reacts by attempting to return to its original travel lane with a counter steer. The HV driver's counter steer reaction time, the time from the trigger point to the attempted counter steer, is denoted as *tRSteer*. The counter steer is defined by a constant jerk in the opposite direction from the original maneuver, *j(tRSteer),* away from the RV. At time *tRSteer*, the HV begins to apply the counter steer, decreasing the lateral speed and lateral acceleration of the HV (slowing the closing rate toward the RV, eventually moving away from the RV). A crash is avoided if $R(t) > 0$ and $v_{Lat} \leq 0$ (v_{Lat} can be zero or negative, which would mean the HV has successfully stopped moving in the direction of the RV and/or has begun to return to its original lane).

Thus, a crash is also avoided if the HV lateral velocity, lateral acceleration, and lateral jerk are all in the lateral direction away from the RV.

7.1.2 Host Braking

An alternate avoidance maneuver would be for the HV to brake (longitudinally) and allow the RV to pass by (longitudinally). This avoidance maneuver would keep lateral motion constant, only decreasing longitudinal velocity and increasing longitudinal range. As the conflict begins, it is identical to the conflict described above; however, the HV reacts by attempting to longitudinally decelerate. The HV driver's brake reaction time, the time from the trigger point to the attempted deceleration, is denoted as *tR*. The deceleration is defined by a constant deceleration in the longitudinal direction, $a_{Lon}(tR)$. At time *tR*, the HV begins to decelerate, decreasing the longitudinal speed of the HV. A crash is avoided if the RV moves longitudinally past the HV. For this avoidance maneuver, it is assumed that the front of the HV and RV are aligned and longitudinal speed difference is negligible (= 0). The longitudinal range needed to allow the RV to pass, is determined by the RV's length.

7.1.3 Host Accelerating

Additionally, the HV may attempt to accelerate, longitudinally, to pass the RV. This conflict is initialized in an identical manner to the other LC/Man conflicts. At the HV driver's reaction time, *tR*, the HV accelerates longitudinally at constant level, $a_{Lon}(tR),$ increasing its longitudinal velocity.

The conflict assumes that the RV is initially positioned parallel to and at the same longitudinal distance as the HV, and the initial longitudinal speed difference between the RV and HV is negligible (= 0). Similar

to the braking reaction, the lateral motion has remained constant throughout the conflict; any avoidance would be the result of the HV passing the RV longitudinally prior to any collision.

7.1.4   Host Braking and Steering

The HV may attempt to combine multiple avoidance maneuvers. The LC/Man conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction times and reaction level inputs are required. During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as described in the previous sections.

7.1.5   Remote Braking

In this kinematic module, it is possible for the RV to be provided with an attempted avoidance maneuver. However, the RV avoidance maneuver is only available when there is an HV steering reaction. The RV may attempt to brake, using the same kinematic equations as described above for HV braking, with similar assumptions (i.e., RV is initially positioned parallel to and at the same longitudinal distance as the HV, and the initial longitudinal speed difference between the RV and HV is negligible (= 0)). The RV may attempt to slow down and allow the HV to pass, and then continue the lane change to avoid any collision. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level.

7.1.6   Remote Steering

In this kinematic module, it is possible for the RV to be provided with an alternative attempted avoidance maneuver. However, the RV avoidance maneuver is only available when there is an HV steering reaction. The RV may attempt to steer, using the same kinematic equations as described above for HV steering, with similar assumptions (i.e., RV is initially positioned parallel to and at the same longitudinal distance as the HV, the initial longitudinal speed difference between the RV and HV is negligible (= 0), and RV has no initial lateral motion). The RV may attempt to steer away from the HV, increasing the lateral range between the HV and RV, and allowing for more time for an HV reaction. The RV reaction is independent of the HV reaction and maneuver, requiring independent inputs for reaction time and braking level.

7.1.7   Remote Braking and Steering

The HV may attempt to combine multiple avoidance maneuvers. The LC/Man conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction times and reaction level inputs are required. During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as described in the previous sections.
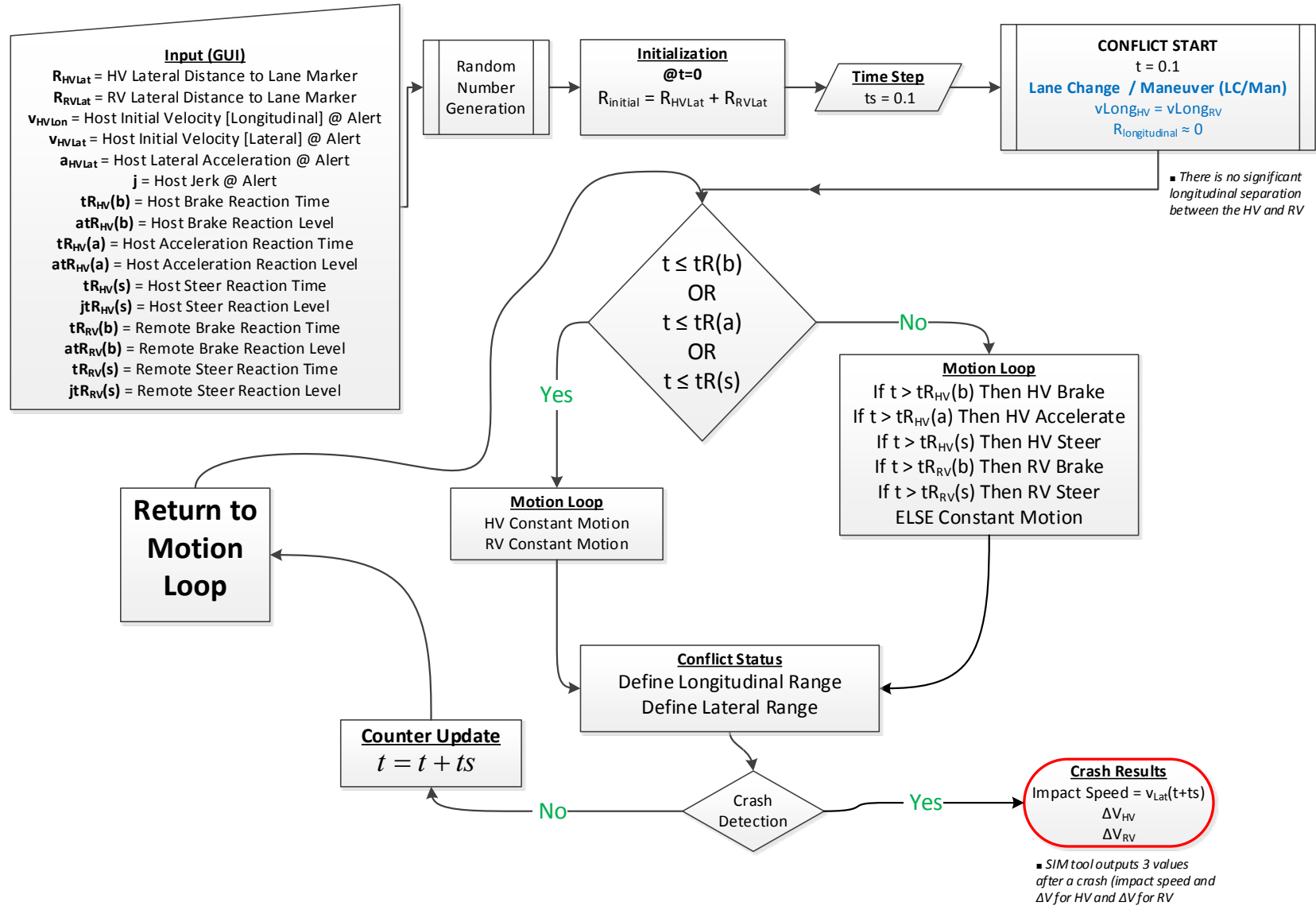
Figure 18. Flowchart for LC/Man Conflict Simulation

Input (GUI)
R_{HVLat} = HV Lateral Distance to Lane Marker
R_{RVLat} = RV Lateral Distance to Lane Marker
v_{HVLon} = Host Initial Velocity [Longitudinal] @ Alert
v_{HVLat} = Host Initial Velocity [Lateral] @ Alert
a_{HVLat} = Host Lateral Acceleration @ Alert
j = Host Jerk @ Alert
$tR_{HV}(b)$ = Host Brake Reaction Time
$atR_{HV}(b)$ = Host Brake Reaction Level
$tR_{HV}(a)$ = Host Acceleration Reaction Time
$atR_{HV}(a)$ = Host Acceleration Reaction Level
$tR_{HV}(s)$ = Host Steer Reaction Time
$jtR_{HV}(s)$ = Host Steer Reaction Level
$tR_{RV}(b)$ = Remote Brake Reaction Time
$atR_{RV}(b)$ = Remote Brake Reaction Level
$tR_{RV}(s)$ = Remote Steer Reaction Time
$jtR_{RV}(s)$ = Remote Steer Reaction Level

Random Number Generation

Initialization @t=0
$R_{initial} = R_{HVLat} + R_{RVLat}$

Time Step ts = 0.1

CONFLICT START
t = 0.1
Lane Change / Maneuver (LC/Man)
$vLong_{HV} = vLong_{RV}$
$R_{longitudinal} \approx 0$

■ *There is no significant longitudinal separation between the HV and RV*

$t \le tR(b)$ OR $t \le tR(a)$ OR $t \le tR(s)$

No

Motion Loop
If t > $tR_{HV}(b)$ Then HV Brake
If t > $tR_{HV}(a)$ Then HV Accelerate
If t > $tR_{HV}(s)$ Then HV Steer
If t > $tR_{RV}(b)$ Then RV Brake
If t > $tR_{RV}(s)$ Then RV Steer
ELSE Constant Motion

Yes

Motion Loop
HV Constant Motion
RV Constant Motion

Return to Motion Loop

Conflict Status
Define Longitudinal Range
Define Lateral Range

Counter Update
$t = t + ts$

Crash Detection

No

Yes

Crash Results
Impact Speed = $v_{Lat}(t+ts)$
ΔV_{HV}
ΔV_{RV}

■ *SIM tool outputs 3 values after a crash (impact speed and ΔV for HV and ΔV for RV)*

48

7.1.8   Treatment

It is assumed that the effectiveness of the BSW/LCW application would come from an improved reaction time and/or improved counter steer by the HV. An improved reaction time can allow for a lower level of counter steer and an improved counter steer can allow for a quicker resolution to the conflict. The LC module only allows a response by the HV. Warning the RV could lead to an unintended conflict (i.e., RV steers into another lane and crashes with a third vehicle; RV stops and is rear-ended by a third vehicle), and is not in the scope of the SIM tool. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

7.2   Delta V Calculation and Impact Modes

In the LC/Man conflict, side-side impact is the only impact mode possible. The kinematic equations are independent of which side the RV is on relative to the HV. Therefore, this impact mode does not distinguish between the HV and the RV (i.e., HV's left side to RV's right side; HV's right side to RV's left side). The kinematics are effectively reduced to one-dimensional kinematics with only HV motion, similar to an LVS conflict. Therefore, ΔV calculations are conducted in the same manner using Equations (21) and (22). The value R_{dot} is determined from the lateral speed at impact of the HV ($R_{dot}(t) = v_{Lat}(t)$, where t = time of impact). This calculation assumes an ideal, inelastic, center-of-mass collision.

8 DNPW/Opposite-Direction Maneuver Kinematic Module

The opposite-direction/passing maneuver (OD/Man) module was developed to estimate the effectiveness of the DNPW application that would sense a potential conflict when a vehicle would encounter a vehicle approaching from the opposite-direction travel lane as it attempts to pass another vehicle traveling in the same direction. This application would benefit from improved range and trajectory information being broadcast through V2V technology. When an HV driver attempts to pass a slower vehicle traveling in the same direction, the application warns the driver if the oncoming RV's speed and range make the passing maneuver unsafe. In addition to warnings, the application also provides advisory information. Even when no passing maneuver is attempted, an "advisory" informs the HV driver if the passing zone is occupied.

The OD/Man conflict can be classified into two cases: passing and non-passing. Both conflicts involve three vehicles: an HV, an RV incident on the HV, and another remote vehicle (RV1) moving parallel to the HV as illustrated in Figure 19. Both cases consist of a two-lane road with opposite-direction travel. Also, in both cases, the event begins with the HV and the RV facing each other in the same lane, and the HV is traveling parallel to the RV1 that is in the other lane.
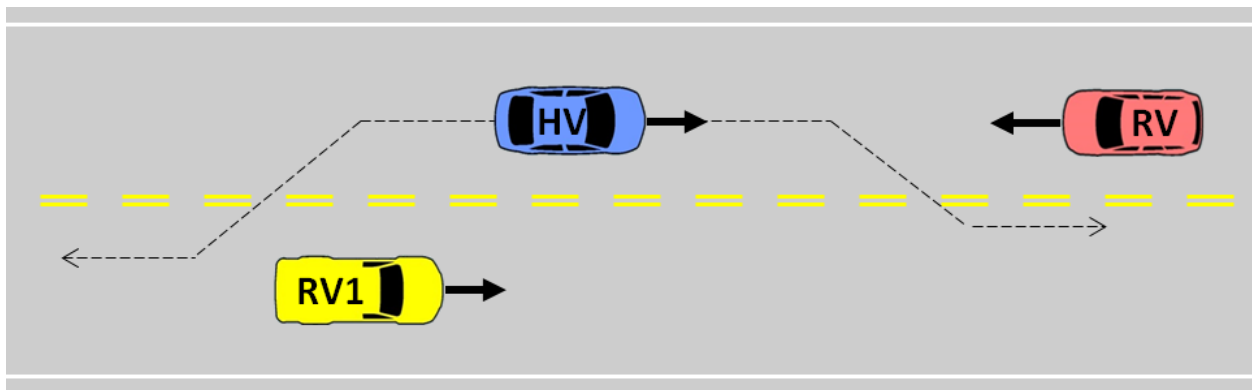
Figure 19. Schematic for an Opposite-Direction/Passing Maneuver Conflict

In the OD/Man conflict, it is assumed that at the start of the conflict, the HV has only longitudinal velocity and no lateral motion (lateral speed is set to 0), as it is parallel to RV1. The HV will only begin lateral motion when it is no longer adjacent to RV1, and a maneuver to return to the proper travel lane is safe, as shown in Figure 20.
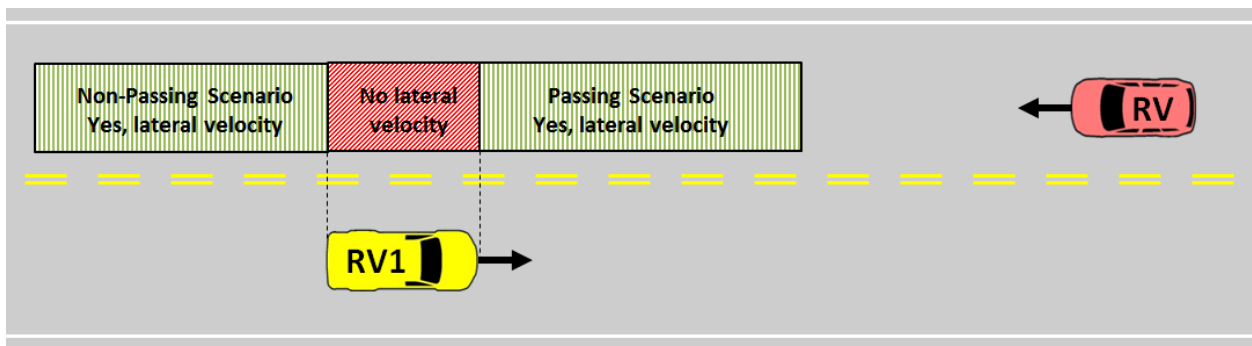
Figure 20. Areas Where the HV Will and Will Not Have Lateral Velocity

In the OD/Man conflict, the HV attempts to avoid a collision with the RV by braking, accelerating, improving their counter steer, braking and steering, or accelerating and steering.[26] For the HV to successfully avoid a collision, it must either brake or accelerate at an appropriate level to clear RV1 and steer successfully back into the appropriate travel lane, behind/ahead of RV1, in order to miss the RV. Table 6 shows the domain of variables needed for the simulation of the OD/Man conflict.

Table 6. OD/Maneuver Domain of Variables for Input into SIM Tool

|	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Host Vehicle Action		Multiple Choice	Passing / Not Passing
	Host Initial Velocity @ Alert	km/h	Numeric	Statistical distribution
	Host Lateral Speed @ Alert	m/s	Numeric	Statistical distribution
	Remote Distance to Lane Marker @ Alert	m	Numeric	Statistical distribution
	Host Distance to Lane Marker @ Alert	m	Numeric	Statistical distribution
	Remote1 Longitudinal Distance	m	Numeric	Statistical distribution
	Remote Longitudinal Distance	m	Numeric	Statistical distribution
	Remote1 Velocity [Longitudinal]	km/h	Numeric	Statistical distribution
	Remote Veloctiy [Longitudinal]	km/h	Numeric	Statistical distribution
HOST Steering	Host Steering Jerk in Control	g/s	Numeric	Statistical distribution
	Host Steering Jerk in Treatment	g/s	Numeric	Statistical distribution
HOST Accelerating	Host Accelerating Force in Control	g	Numeric	Statistical distribution
	Host Accelerating Force in Treatment	g	Numeric	Statistical distribution

*Multiple Choice allows the user to choose only one of a predefined set of options

8.1 OD/Maneuver - Passing

In the OD/Man – Passing conflict, the HV attempts to complete the passing maneuver of RV1 prior to returning into the appropriate travel lane. In this conflict, the attempted avoidance maneuver is to improve accelerating and/or counter steering in order to return to the proper travel lane.

8.1.1 Host Accelerating

The conflict begins with the HV traveling toward the RV at some positive longitudinal speed, v_{HVLon}. Over time, the HV travels some longitudinal distance, d_{HV} ($d_{HV} = 0$ at t = 0). The HV starts with a longitudinal acceleration, a_{HV}, that is positive for the passing case. The HV starts with a lateral distance, d_{HVLat} ($d_{HVLat} = 0$ at t = 0), and negative lateral distance, R_{HVLat}, from the lane marker.[27] The RV starts heading toward the HV with a negative longitudinal speed, v_{RVLon}, and is initially placed at a positive longitudinal distance, R_{RVLon}. The RV1 begins traveling parallel to the HV with a positive longitudinal speed, v_{R1Lon}, and starts at a longitudinal distance, d_{RV1Lon}, and lateral distance R_{RV1Lat}. The RV begins with a negative lateral distance, R_{RVLat}, from the lane marker.

Figure 21 defines some of the key variables used in the OD/Man – Passing conflict.

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[26] The HV may not collide with RV1, as the HV will not begin lateral motion until it has safely longitudinally cleared RV1.
[27] d_{HVLat} is a dimension to measure the lateral distance traveled by the HV and is measured from the initial lateral position of the HV.
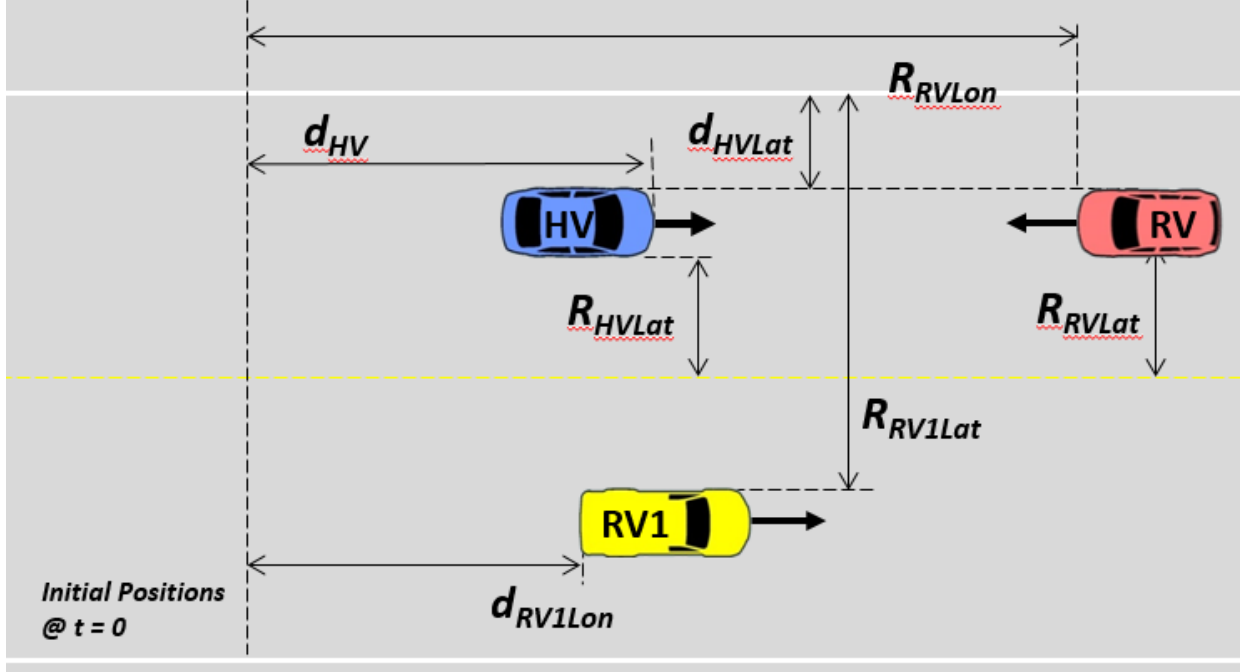
Figure 21. Identification of Parameters for the OD/Man Simulation

In this conflict, the HV initially moves forward with some longitudinal acceleration (the lateral speed is taken as zero) in the conflict zone, and attempts to move directly in front of the RV1 without being struck by the RV (i.e., suffering a front-to-front collision). While the HV is next to RV1, the HV maintains a constant lateral distance from the road centerline. The RV1 maintains a constant lateral distance from the road centerline throughout the event. The longitudinal distance between the HV and RV decreases due to the positive HV velocity and the negative RV velocity. This distance continues decreasing due to the positive HV acceleration, toward the RV. When the back of the HV is at the same longitudinal position as the front of RV1 (i.e., $d_{HV} > d_{RV1}$, while accounting for vehicle body sizes) then the HV begins turning positively (toward the RV1) by using a jerk, j. In this case, the HV's lateral speed, v_{HVLat}, increases, hence the HV's lateral distance also increases, moving toward RV1. For the acceleration avoidance maneuver, HV acceleration may vary between control and treatment, while the steering rate remains constant.

The HV returns safely if the lateral distance of the left side of the HV is equal or greater than the lateral distance of the left side of the RV1 (i.e., $R_{HVLat} \geq R_{RV1Lat}$), and the HV has not collided with the RV. In that case, the conflict ends without a collision. Otherwise, there is a front-to-front collision between the HV and RV.

8.1.2 Host Steering

An alternate avoidance maneuver would be for the HV to improve their steering rate, in order to return to the appropriate travel lane. The conflict is run identically to the conflict described above; however, the acceleration remains constant between control and treatment, and the steering rate varies.

In the passing conflict, the longitudinal distance between the HV and RV initially decreases due to the positive v_{HVLon} and the negative v_{RVLon}. When the back of the HV is at the same longitudinal position as the front of RV1, then the HV begins turning positively (toward the RV1) by using a counter jerk, j. In this case, the HV's lateral speed, v_{HVLat}, increases, hence the HV's lateral distance also increases.

52

8.1.3   Host Accelerating and Steering

The OD/Man – Passing conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction level inputs are required.[28] During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as described in the previous sections.

8.1.4   Treatment

System effectiveness in OD/Man – Passing is derived from an improvement in driver reaction level. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

8.2   OD/Maneuver – Non-Passing

In the OD/Man – Non-Passing conflict, the HV attempts to abort the passing maneuver of RV1 prior to returning into the appropriate travel lane. In this conflict, the attempted avoidance maneuver is to improve braking and/or counter steering in order to return to the proper travel lane.

8.2.1   Host Braking

The conflict begins identical to the passing conflict , with the HV traveling toward the RV at some positive longitudinal speed, v_{HVLon}. Over time, the HV travels some longitudinal distance, d_{HV} ($d_{HV} = 0$ at $t = 0$). In the non-passing conflict , the HV has a longitudinal acceleration, a_{HV}, which is negative (as opposed to positive in the passing conflict). The HV starts with a lateral distance, d_{HVLat} ($d_{HVLat} = 0$ at $t = 0$), and negative lateral distance, R_{HVLat}, from the lane marker.[29] The RV starts heading toward the HV with a negative longitudinal speed, v_{RVLon}, and is initially placed at a positive longitudinal distance, R_{RVLon}. The RV1 begins traveling parallel to the HV with a positive longitudinal speed, v_{R1Lon}, and starts at a longitudinal distance, d_{RV1Lon}, and lateral distance R_{RV1Lat}. The RV begins with a negative lateral distance, R_{RVLat}, from the lane marker.

In this conflict, the HV initially moves backward with some longitudinal braking (the lateral speed is taken as zero) in the conflict zone, and attempts to move directly behind the RV1 without being struck (i.e., suffering a front-to-front collision). When the HV's front end is at the same longitudinal distance as the RV1's rear end, the HV initiates a jerk to its right in an attempt to avoid a collision with the incident RV and move behind the RV1.

The HV returns safely if the lateral distance of the left side of the HV is equal or greater than the lateral distance of the left side of the RV1 (i.e., $R_{HVLat} \geq R_{RV1Lat}$) and the HV has not collided with the RV. In that case, the conflict ends without a collision. Otherwise, there is a front-to-front collision between the HV and RV.

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[28] Acceleration levels and steering rate levels are always required. However, when only one avoidance maneuver is selected, the non-selected reaction level remains constant between control and treatment. If both avoidance maneuvers are selected, both reaction levels will vary between control and treatment.

[29] h_{Lat} is a dimension to measure the lateral distance traveled by the HV and is measured from the initial lateral position of the HV.

8.2.2 Host Steering

In the passing conflict, the longitudinal distance between the HV and RV initially decreases due to the positive v_{HVLon} and the negative v_{RVLon}. However, in this case, the longitudinal acceleration, a_{HV}, of the HV is negative, hence the longitudinal distance between the HV and RV can *increase*. When the front of the HV is at the same longitudinal position as the back of RV1, then the HV begins turning positively (toward the RV1) by using a counter jerk, j. In this case, the HV's lateral speed, v_{HVLat}, increases, hence the HV's lateral distance also increases.

8.2.3 Host Braking and Steering

The OD/Man – Non-Passing conflict allows for the use of independent or concurrent avoidance maneuvers. When multiple avoidance maneuvers are desired, multiple reaction level inputs are required.[30] During the simulation, each avoidance maneuver is enacted appropriately, independent of one another. Note that because of this independence, no consequences of combined avoidance maneuvers are modeled (i.e., spin outs when combining heavy braking and steering together). The conflict and avoidance maneuvers are modeled as described in the previous sections.

8.2.4 Treatment

It is assumed that the effectiveness of the DNPW application would come from an improved longitudinal acceleration/deceleration and/or improved counter steer by the HV. An improved longitudinal acceleration/deceleration can allow for a lower level of counter steer. The OD/Man conflict only allows a response by the HV. Warning the RV could lead to an unintended conflict (i.e., RV steers into another lane and crashes with the RV1) and is not in the scope of the SIM tool. At the completion of trials in all treatments, the SIM tool outputs the results detailed in Section 3.3.

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[30] Braking levels and steering rate levels are always required. However, when only one avoidance maneuver is selected, the non-selected reaction level remains constant between control and treatment. If both avoidance maneuvers are selected, both reaction levels will vary between control and treatment.
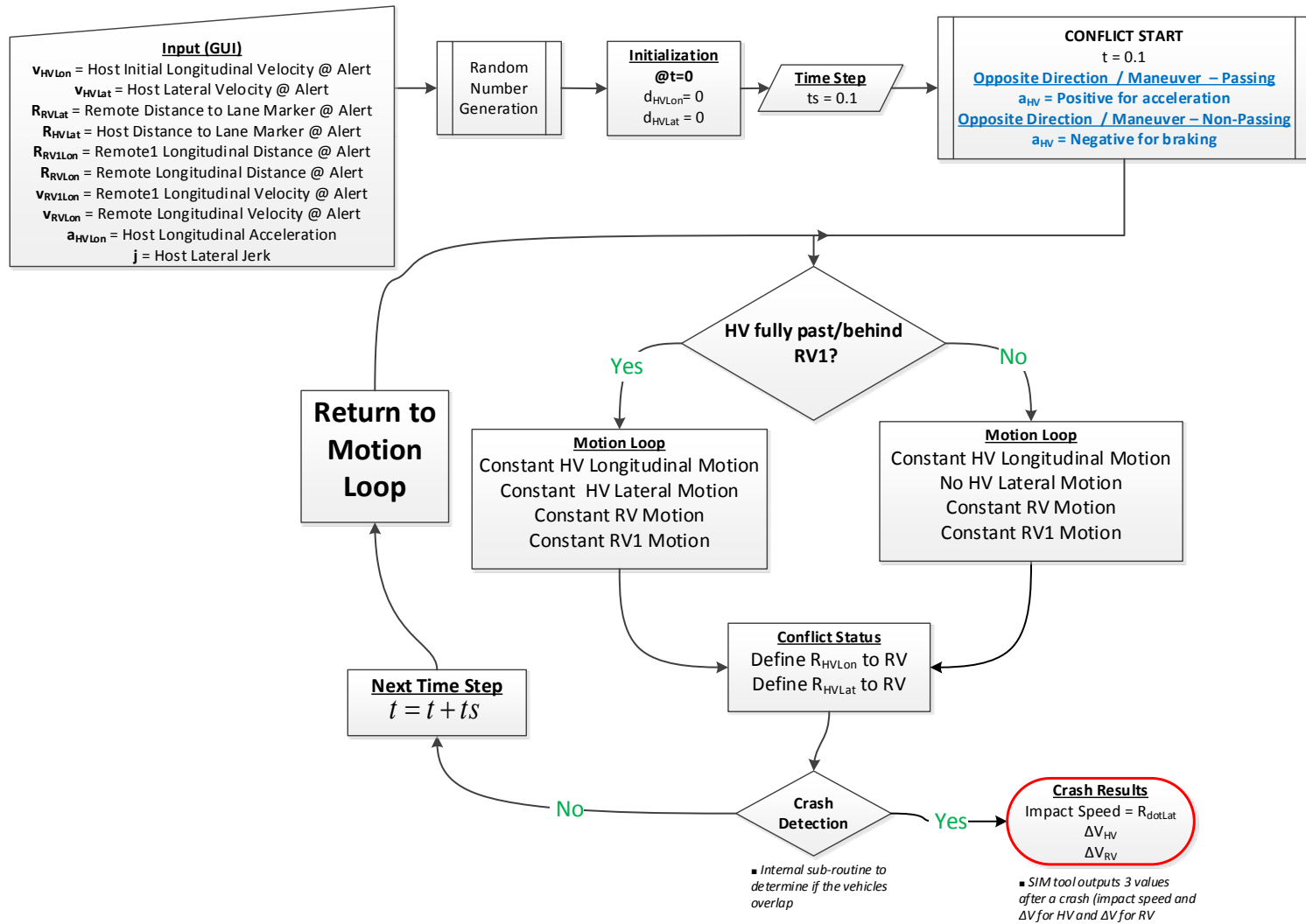
Figure 22. Flowchart for OD/Man Simulation

8.3 Delta V Calculation and Impact Modes

In the OD/Man conflict, ΔV calculations are conducted in the same manner as Equations (21) and (22). The value R_{dot} is determined from the magnitude of the vector difference of the HV and RV at impact (i.e., using the front-to-front variation as described in Equation (37)). This calculation assumes an ideal, inelastic, center-of-mass collision.

9 Opposite-Direction/No-Maneuver Kinematic Module

9.1 Opposite-Direction/No-Maneuver Conflict

The opposite direction/no-maneuver (OD/No Man) module consists of two vehicles approaching each other on a two-lane road with opposite direction travel and the HV drifts laterally into the opposite-direction travel lane, as seen in Figure 23. Currently, there is no V2V-based safety application as a countermeasure for the OD/no-maneuver pre-crash scenario.

The RV maintains a constant lateral distance from the road median throughout the event. The HV begins the event with an initial lateral distance from the road median. One vehicle (the HV) crosses over the median into the other vehicle's (the RV) lane. There are two possible collision cases: a front-to-front collision or a side-to-side collision, which give quite different performance results. In the countermeasure (treatment) condition, a jerk is used to correct the drift and avoid a crash by steering and returning the HV to the proper lane. The HV may attempt to avoid the collision by steering back into the original travel lane. Table 7 shows the domain of variables needed for the simulation of the OD/No Man module in the SIM tool.

Table 7. OD/No-Maneuver Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	Host Velocity [Longitudinal]	km/h	Numeric	Statistical distribution
	Host Velocity [Lateral] @ Alert	m/	Numeric	Statistical distribution
	Remote Velocity [Longitudinal]	km/h	Numeric	Statistical distribution
	Remote Distance to Lane Marker **@ Alert**	m	Numeric	Statistical distribution
	Remote Distance [Longitudinal]	m	Numeric	Statistical distribution
	Host Distance to Lane Marker **@ Alert**	m	Numeric	Statistical distribution
HOST Steering	Host Counter Steering [Lateral] Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host Counter Steering [Lateral] Jerk in **Control**	g/s	Numeric	Statistical distribution
	Host Counter Steering [Lateral] Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host Counter Steering [Lateral] Jerk in *Treatment*	g/s	Numeric	Statistical distribution

9.1.1 Host Steering

The conflict begins with the HV traveling toward the RV at some positive longitudinal speed, v_{HVLon}, and lateral speed, v_{HVLat}, toward the lane marker separating the HV and RV. The HV also starts with some lateral distance, R_{HVLat}, from the lane marker. The RV begins traveling toward the HV with a negative longitudinal speed, v_{RVLon}, and with lateral distance, R_{RVLat}, from the lane marker. Also at the start, the RV has initial longitudinal distance, $R_{RVLon}(=0)$, and the HV has initial longitudinal distance $d_{HVLon}(=0)$ and initial lateral distance $d_{HVLat}(=0)$.

Figure 23 illustrates the key variables for the OD/No Man kinematic module.
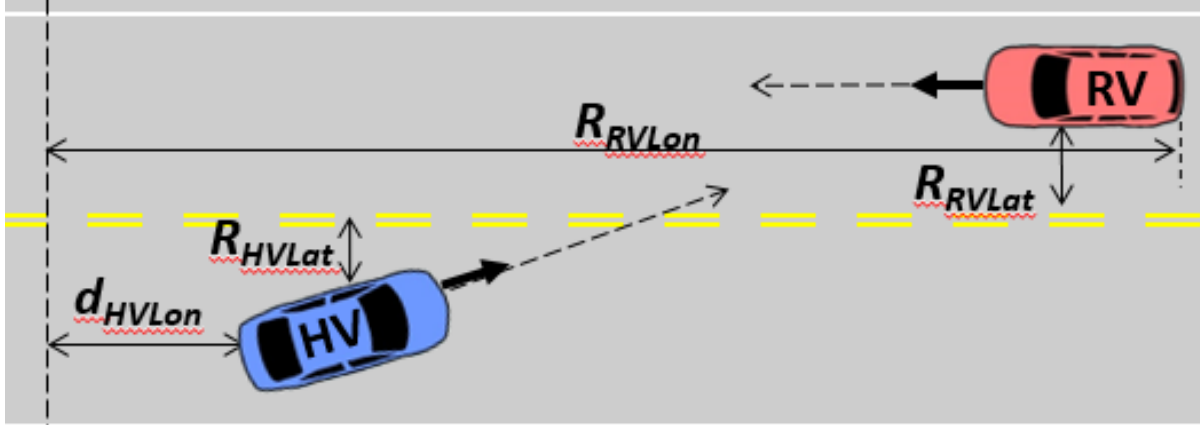
Figure 23. Vehicle Configuration for OD/No-Maneuver Pre-Crash Scenario

When the conflict starts, the distance between the HV and RV is decreasing both laterally, due to a negative HV lateral speed, v_{HVLat}, and longitudinally, due to the positive HV longitudinal speed, v_{HVLon}, and the negative RV longitudinal speed, v_{RVLon}. The relative distance continues decreasing at a constant rate unless the reaction time, tR, is reached, or the longitudinal separation between HV and RV decreases to zero (this means a crash has occurred). If tR is reached, then the HV steers laterally using a positive counter jerk (j) and the magnitude of v_{HVLat} begins to decrease. If a collision occurs and the change in the lateral position of the HV becomes greater than $R_{HVLat} + R_{RVLat}$ (this means there is lateral overlap), then there is a front-to-front collision; otherwise, the two vehicles collide side to side.

9.1.2 *Treatment*

It is assumed that the effectiveness in an OD/No Man application would come from an improved reaction time and/or improved counter steer by the HV. An improved reaction time can allow for a lower level of counter steer and an improved counter steer can allow for a quicker resolution to the conflict. The OD/No Man module only allows a response by the HV. Warning the RV could lead to an unintended and/or subsequent conflict and is not in the scope of the SIM tool. At the completion of trials in all treatment conditions, the SIM tool outputs the results detailed in Section 3.3.

9.2 Delta V Calculation

In the OD/No Man module, ΔV calculations are conducted in the same manner as Equations (24) and (25). The value R_{dot} for the side-side impact mode is determined as v_{Lat}. The value R_{dot} for the front-front impact mode is determined as $v_{Lon} + vR_{Lon}$. This calculation assumes an ideal, inelastic, center-of-mass collision.

Figure 24 illustrates the simulation of the OD/No Man conflict.

Figure 24. Flowchart for OD/No-Maneuver Simulation

10 EEBL/Longitudinal Queue Kinematic Module

The longitudinal queue kinematic module was developed to estimate the effectiveness of the Emergency Electronic Brake Light (EEBL) application. The longitudinal queue models 10 vehicles traveling in a straight line, oriented front to back, initialized with initial distances between v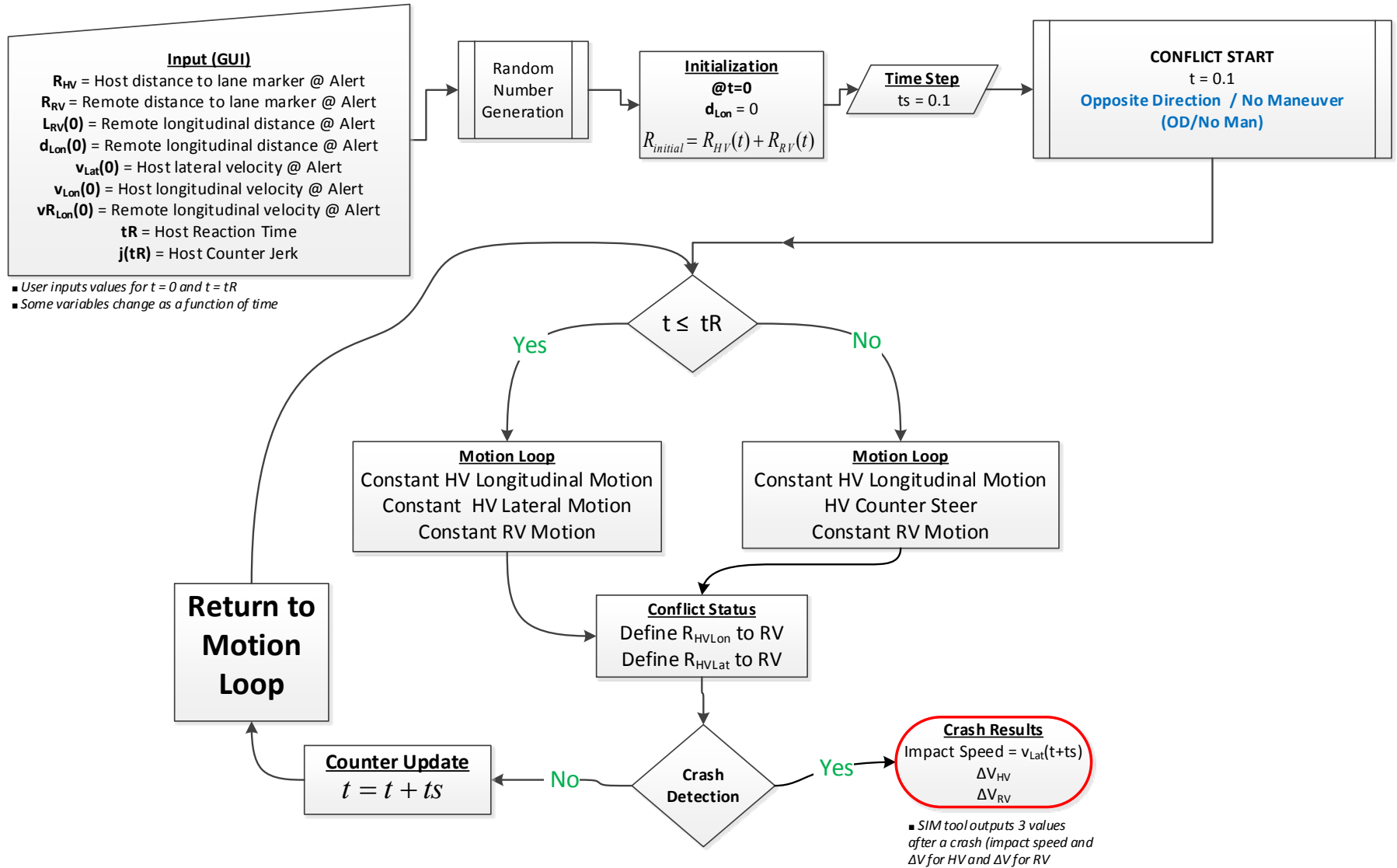ehicles and initial velocities for each vehicle. The lead vehicle in the queue is labeled V_{10}, while the last vehicle in the queue is labeled, V_1. The following vehicles may attempt to avoid a collision with the vehicle in front by braking or allowing automatic braking to begin.

Each pair of vehicles (vehicles aligned adjacently, front to back) experiences a typical rear-end driving conflict, similar to the LVM or LVD described in Section 4. The EEBL application warns the drivers of the following vehicles (all are considered HVs) of the first vehicle's braking and allows for earlier braking and/or applies automatic braking. Table 8 lists the domain of variables needed for the longitudinal queue module in the SIM tool.

Table 8. Queue Domain of Variables for Input into SIM Tool

	Variable	Units	Input Type	Notes
Conflict	Crash Module		Multiple Choice	Main Crash Module
	Pre-Crash Scenario		Multiple Choice	Pre-Crash Scenario
	Avoidance Maneuver		Multiple Choice	Attempted Avoidance Maneuver(s)
	EEBL Active		Binary	With our Without
Vehicle Parameters	Host [Vehicle 1] Initial Distance	m	Numeric	Statistical distribution
	Host [Vehicle 1] Initial Velocity	km/h	Numeric	Statistical distribution
	Host [Vehicle 1] Braking Reaction Time in **Control**	s	Numeric	Statistical distribution
	Host [Vehicle 1] Braking Force in **Control**	g	Numeric	Statistical distribution
	Host [Vehicle 1] Braking Reaction Time in *Treatment*	s	Numeric	Statistical distribution
	Host [Vehicle 1] Braking Force in *Treatment*	g	Numeric	Statistical distribution
System Parameters	Host to Lead1 TTC Warning	s	Numeric	Statistical distribution
	Host to Lead1 Stage 1 Autobrake TTC Activation	s	Numeric	Statistical distribution
	Host to Lead1 Stage 1 Autobraking Force	g	Numeric	Statistical distribution
	Host to Lead1 Stage 2 Autobrake TTC Activation	s	Numeric	Statistical distribution
	Host to Lead1 Stage 2 Autobraking Force	g	Numeric	Statistical distribution
Additional Vehicles	Additional Vehicles may be added with parallel Vehicle and System Parameters. Up to 10 total vehicles may be added.			

*Multiple Choice allows the user to choose only one of a predefined set of options

Similar to the FCW section described earlier, the longitudinal queue module is capable of evaluating incremental system effectiveness when automatic control is introduced into each vehicle's crash avoidance system.[31] This module follows the same kinematic principles as the rear-end crash module, including baseline and treatment conditions. The SIM queue tool does not allow for the implementation of two-staged automatic braking. The configuration conditions are defined for all vehicle pairs.

10.1 Moving Rear-End Queue

The longitudinal queue models 10 vehicles with initial distances, d_i (where the vehicle number i can be 1 through 10), between vehicles. Each vehicle is assigned initial velocities, v_i (where the vehicle number i can be 1 through 10), brake reaction times, and braking levels. When the lead vehicle, V_{10}, first brakes, the delay (i.e., reaction time countdown) for the second vehicle, V_9, is started. Once that second vehicle has properly reacted to the braking of the first vehicle, the second vehicle starts braking at a constant level. Thus, for the non-EEBL case, each vehicle subsequently brakes once the delay for the vehicle in-front expires (i.e., a vehicle only reacts to the single vehicle in front of that specific vehicle). For the

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[31] This module allows for each vehicle to have automatic control or not.

EEBL treatment case, all vehicles brake simultaneously once the delay for the second vehicle expires (i.e., all vehicles behind the lead vehicle react simultaneously).

Previous rear-end conflicts were described in Section 4 above. Those conflicts involve only two vehicles and a single event, in the moving rear-end queue; here, there are 10 vehicles in a longitudinal queue, creating the potential for multiple conflicts. All adjacent vehicles in the queue are said to be involved in a conflict. These conflicts could be modeled as LVS, LVM, or LVD depending on the initial inputs and timing of the simulation.

10.1.1 Lead Vehicle(s) Braking

When EEBL is turned off, the reaction times propagate from the first lead vehicle (at the beginning of the queue) to the last vehicle at the end of the queue. That is, the reaction times time out sequentially from the beginning to the end of the queue: once a leading vehicle's reaction time times out, the following vehicle's reaction time then starts to count down and decrease.

A detailed breakdown and analysis of the governing kinematic equations is given in Section 4. The SIM kinematic modules deploy a time-step iterative process in lieu of closed-form equations. Each vehicle pair conflict is defined by initial distances, d_i, where the vehicle number i can be 0 through 8 (see Figure 25 for the case of four vehicles with i equal to 0, 1, and 2), initial longitudinal velocities, v_i, (where the vehicle number i can be 0 through 9), the initial longitudinal decelerations, a_i, (where the vehicle number i can be 0 through 9), and the initial reaction times, t_i, (where the vehicle number i can be 0 through 8, since the lead vehicle reaction time is immediate). The crash speed for each pair is, R_{doti}, where the vehicle number i can be 0 through 8, since there are only 9 pairs.
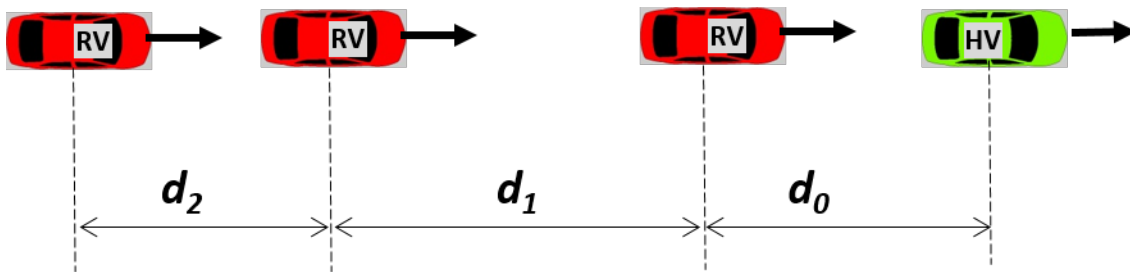
Figure 25. EEBL Geometry

R_{doti} is determined implicitly by the SIM code: the relative speed between $i+1$ and i speeds.

$$R_{doti}(t) = |v_{i+1}(t) - v_i(t)| \qquad (39)$$

To initialize the conflict, the second vehicle is placed at some distance behind the first vehicle. The third vehicle is then placed at some distance behind the second vehicle. This process is continued until the tenth vehicle is then placed at some distance behind the ninth vehicle. In general the initial separation distances between each vehicle pair can be variable.

A crash is defined when a vehicle pair overlaps on the same space and one vehicle has a speed greater than zero. This does not conclude one conflict or one instance in the SIM tool simulation in general since a run can now consist of multiple collisions. This is different from all other conflicts covered in this document, where a single crash terminates a trial. One conflict, or instance, is completed when all vehicles have come to a stop.

There are three main outputs for the total of all runs (a run generally consists of multiple crashes). First, each vehicle's collision speed and ΔV is recorded for each of its collisions. Second, the number of different crash types (0 car crash, 1 car crash, 2 car crash, 3 car crash, 4 car crash, 5 car crash, 6 car crash, 7 car crash, 8 car crash, 9 car crash, or 10 car crash) is recorded for each run. Third, the number of vehicles involved in each of these different crash types is recorded for each run.

The number of vehicles involved in a crash run depends on the number of crashes in that run. A few examples include:

- For 0 crashes, there are 0 vehicles involved;
- For 1 crash, there must be 2 vehicles;
- For 2 crashes, there could be 3 or 4 vehicles;
- For 8 crashes, there could be 9 or 10 vehicles; and
- For 9 crashes, there are 10 vehicles.

10.1.2 Treatment

When EEBL is turned on, all vehicles brake simultaneously once the delay for the second vehicle expires.

EEBL-off illustrates Treatment 0 (baseline condition); EEBL-on illustrates Treatment 1 condition as described in Section 3.4. For both Treatments 0 and 1, the SIM tool assumes a pair of vehicles would benefit from improved driver reaction time and/or braking level. Improvement in driver reaction time would allow for a shorter distance traveled during the reaction time, allowing for a longer vehicle braking time. An improvement in any vehicles' braking force, would lead to a decrease in stopping distance, which could be necessary to avoid a crash.

However, Treatment 1 also assumes that a global immediate reaction time will result in a decrease in the number of total crashes for a given run. That is, for Treatment 1, once the second vehicle reaction time expires, all vehicles brake simultaneously. This means that all vehicles (except the second) brake with maximum (initial) separation distance with the vehicle directly in front of them. This is in contrast to Treatment 0, where each separation distance between any two vehicles at the time of braking is less than the initial separation between the two vehicles due to deceleration of the leading vehicle of the two vehicles. Thus, Treatment 1 is an improvement in braking distance between all (except the first) pairs of vehicles and hence allows for longer vehicle braking time.

10.2 Delta V Calculation and Impact Modes

All collisions are treated as inelastic. Thus, after the collision of two vehicles, the vehicles move together as a unit that has a total mass equal to the sum of the two vehicle masses and moves with some new velocity that is determined by the conservation of momentum for inelastic collisions. Thus, in general, a collision consists initially of, say, n vehicles of total mass m_i and speed $v_i(tc)$ traveling as a single unit colliding with, say, m vehicles of total mass m_{i+1} and speed $v_{i+1}(tc)$ traveling as a unit and consists finally as a single unit of n+m vehicles moving with final velocity determined by the conservation of momentum for inelastic collisions with final mass equal to the sum of m_i and m_{i+1}. Thus, after collision, the velocity of each of the vehicles in the final group are equal and are given by Equation (40), for example, where, t_c is the time at collision, t is the final time, and j is the number of the first vehicle of the group. Similarly, the final acceleration for each of the vehicles is approximated by that of the smaller vehicle number and is given by Equation (41).

$$v_j(t) = v_{j+1}(t) = \cdots = v_i(t) = v_{i+1}(t) = \cdots = v_{n+m}(t) \tag{40}$$

$$= \frac{m_i(t_c)v_i(t_c)}{m_i(t_c) + m_{i+1}(t_c)} + \frac{m_{i+1}(t_c)v_{i+1}(t_c)}{m_i(t_c) + m_{i+1}(t_c)}$$

$$a_j(t) = a_{j+1}(t) = \cdots = a_i(t) = \cdots = a_{n+m}(t) \tag{41}$$

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Appendix A: SIM Tool Validation Using EDR Data

To validate the SIM tool's kinematic modules, CDS cases from several years (2008-2013) were selected and reviewed. Case files were analyzed for inclusion in the SIM tool target crash population, meaning the case could have been simulated in the SIM tool. Criteria include:

- Two vehicles involved;
- Fit pre-crash scenario criteria (rear-end, SCP, LTAP/OD, LC, and OD); and
- Both vehicles involved had EDR data.

A case list was compiled, and crashes were reconstructed, based on available EDR data that include discrete information on the seconds (i.e., 5 seconds or 10 seconds) leading up to the crash, including vehicle speed, throttle input, binary brake inputs, the crash results, and ΔV values. Reconstructions detailed information on braking activation times and braking levels. Results from CDS files, reconstructions, and the SIM tool were compared.

A.1 Model

To model vehicle motion, we describe it using a rectilinear (straight), point-mass (no torsional inertia, no rotation), constant acceleration equation:

$$v_{final}(t) = v_{initial} + a(t) \times t \tag{42}$$

where v is the speed and $a(t)$ is the constant value of acceleration that is applied at time t and maintained until the collision. If there is no braking, the acceleration is 0. As for the displacement of a vehicle, the assumption of constant acceleration implies that over time the speed will change linearly. This linear change allows us to model the displacement over a given time interval as:

$$d(t) = d(t-1) + \frac{v(t-1) + v(t)}{2} \times \Delta t \tag{43}$$

where $d(t)$ is the vehicle displacement at a given time, and because EDR data is sampled once every second, Δt is 1 second. We use the conservation of linear momentum principle to compute the post-crash speed and change in speed of each vehicle:

$$(m_{HV} \times v_{HV} + m_{RV} \times v_{RV})_{before} = (m_{HV} \times v_{HV} + m_{RV} \times v_{RV})_{after} \tag{44}$$

where:

        m ≡ mass of vehicle

        v ≡ velocity of vehicle

A.1.1 Inherent Assumptions in Model

The vehicle motion model assumes <u>straight motion</u>. When working with rear-end crashes on straight roads, this assumption does not change the motion before and after the impact. The model assumes a <u>point mass</u>. Given that we are concerned with impact speeds and changes in speeds after the impact, and given that for rear-end crashes the longitudinal axes of the vehicles are nearly collinear (another assumption, which can be checked in each CDS dataset by ensuring that neither vehicle spun after the crash), this assumption does not change motion before and after the impact. The model assumes <u>constant</u>

acceleration. If the vehicle speeds in the EDR data are either nearly constant, or change roughly linearly with time, the constant-acceleration assumption will not change vehicle motion. The cases we have examined have nearly constant speeds, or speeds that change roughly linearly with time. The conservation of linear momentum equation presented above assumes rectilinear motion, point masses, and a shared speed after the crash, the latter implying that vehicles will not bounce during the crash and thus have the same speed (although not the same change in speed) after the crash. Light vehicles have crumple zones that absorb kinetic energy during a crash. In the rear-end collisions we are modeling, we expect the crumple zones to absorb all the kinetic energy so that the impact never results in a rigid structure recoiling from another rigid structure.

The vehicle motion models are developed using EDR data. An example of the method is provided in Section A.1.2. Although we worked backwards in time from a crash to estimate and model the speeds and distances of each vehicle before the crash, we did not then work forward in time with the model to check that the modeled motion resulted in a crash. The vehicles crashed, which is why they are in the crash database. Small changes in the speed introduced by assuming a constant acceleration or an acceleration applied at a sampling time are just that, small changes. The crash still occurred and the speed differences in the model versus actual crash are small enough to not affect ΔV estimates. Furthermore, the backwards-in-time motion resulted from specifying an initial range of 0, for both rear-end and straight-crossing-path crashes. The initial range of 0 meant that modeled motion began with a crash and, as noted, worked backwards to estimate pre-crash speeds and ranges. Because the model began with a crash, there was no need to simulate modeled vehicle motion forward in time to ensure that the modeled motion still crashed. Indeed, it is valuable to test independently that the modeled motion leads to a crash. The SIM tool provides a means to test modeled motion for crashes.

A.1.2 Parameterizing Model with EDR Data

To model a collision from EDR data, we start at the impact, calling this time $t(0)$ and assuming each vehicle's EDR saved the data from the same previous 5 seconds. Using the displacement and speed equations above, we work backwards, second by second, from the impact time to 5 seconds before the impact. Figure 26 shows the geometry for parameterizing the motion model. Note that the Δx values in the figure are negative: vehicle motion is positive in the right direction (as in the typical coordinate frame with x to the right) and because the impact occurs at $t = 0$, each vehicle is left of this point at times leading up to the crash.
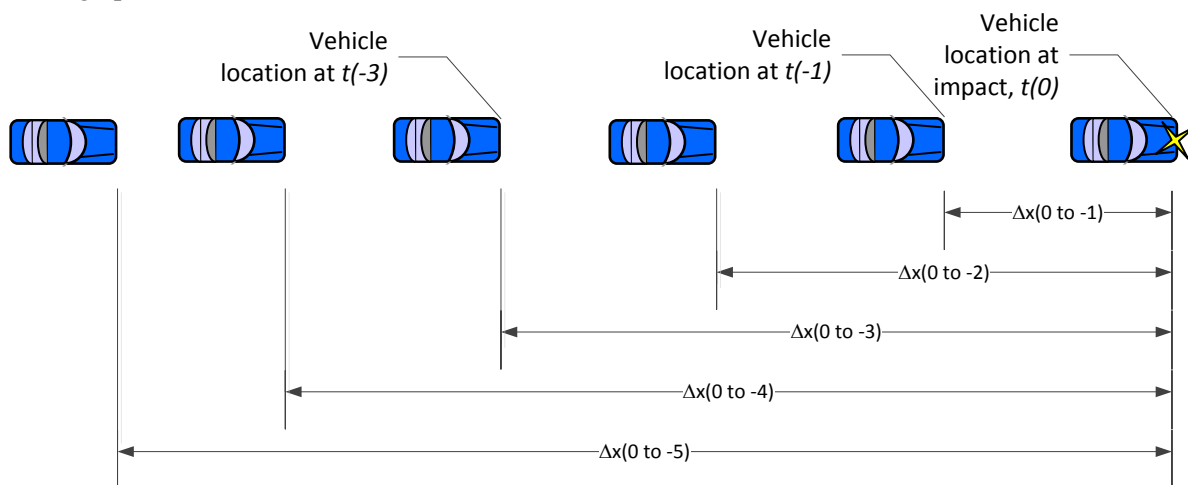
Figure 26. Geometry for Parameterizing Vehicle Motion Model

Prior to reconstructing crashes, we will use the decelerating-vehicle data in Table 9 to show how EDR data can parameterize the kinematic model in Equations (42) and (43) at the beginning of this section.

Table 9. EDR Data and Modeled Data

Time	EDR speed (ft/sec)	Modeled Deceleration (ft/sec²)	Modeled speed (ft/sec)	$V_{EDR} - V_{model}$ (ft/sec)
-5	54.3	13.6	54.3	0.0
-4	42.5	13.6	40.7	1.8
-3	29.3	13.6	27.1	2.2
-2	14.7	13.6	13.6	1.1
-1	4.4	13.6	0	4.4
0		0	0	

Table 9 contains a set of EDR data for a lead vehicle in an LVD case, and the data used to model this motion. Although the model in Equation (42) imposes no condition regarding acceleration, $a(t)$, varying from one time to another, we model vehicle motion as having either no acceleration (constant speed) or a constant value of acceleration over some time. This simplifies the motion and the understanding of the motion. The EDR speed data in Table 9 show a steady decrease in the vehicle speed. When the pre-crash data end at $t = -1$, the vehicle was traveling at 4.4 feet per second (3 mph). Setting this value to 0 at $t = -1$ simplifies the motion model and introduces little error in speed or distance. The third column in the table, the modeled deceleration, results from dividing the modeled change in speed (54.3 ft/sec to 0 ft/sec) over the change in time (4 seconds), resulting in a deceleration of 13.6 ft/sec². By substituting this value into Equation (42), we can calculate speed versus time for the modeled motion. Figure 27 plots EDR speed data and modeled speed data, showing good agreement between the two.
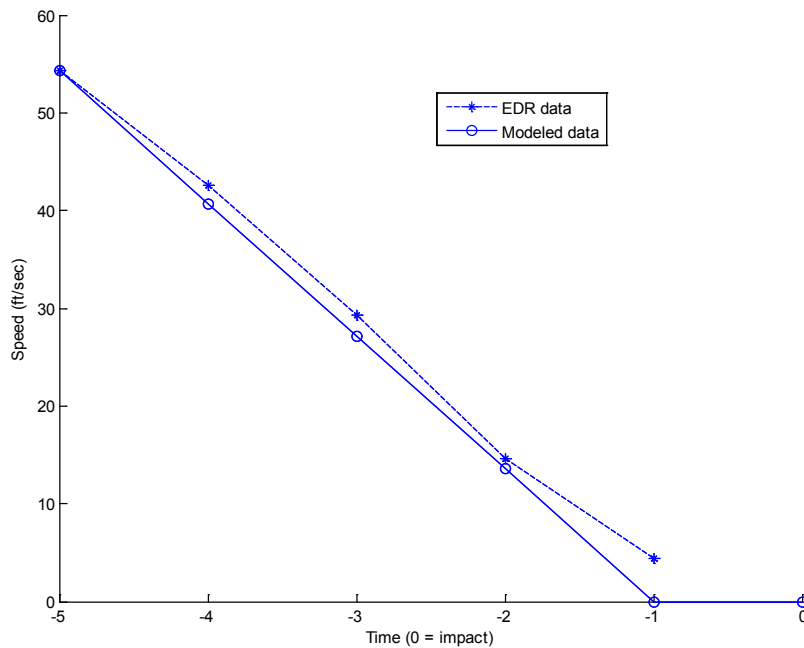
Figure 27. EDR Speed Data and Modeled Speed Data

The modeled speed data in Table 9 can be used to estimate the location of the vehicle prior to the crash, where "location" is the distance to the point of impact. By inserting the modeled speed data into Equation (43), we can work backwards from the point of impact and estimate how far the vehicle traveled over each preceding second. From time $t = -1$ to $t = 0$, the vehicle was not moving, so there was no displacement over that period. From time $t = -2$ to $t = -1$, the preceding second, the speed changed from 13.6 ft/sec to 0 ft/sec. The average speed was 6.8 feet/sec, and this average multiplied by 1 second results in a displacement of 6.8 feet, the vehicle's location 2 seconds prior to the collision. We continue working backwards in time up to the time $t = -5$. Table 10 shows the modeled speed and distance values, and Figure 28 plots the distance values on the left axis and the modeled deceleration values on the right axis.

Table 10. Modeled Speed and Distance Data

Time	Modeled speed (ft/sec)	Modeled change in distance (ft)	Modeled distance from impact location (ft)
-5	54.3	47.5	-108.5
-4	40.7	33.9	-61.1
-3	27.1	20.4	-27.1
-2	13.6	6.8	-6.8
-1	0	0	0
0	0	0	0
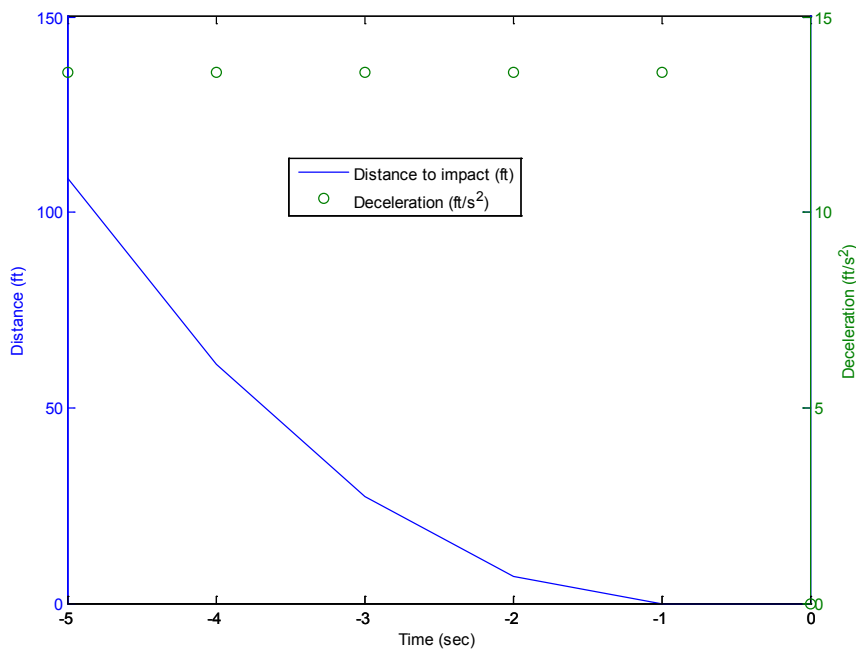
Figure 28. Modeled Range Data (ft) and Deceleration (ft/sec²)

For two vehicles in a crash, we create separate tables of deceleration, speed, and distance data. Prior to the impact, the host vehicle will be farther from the impact site than the lead vehicle. The difference in the distance data is the range between the host and the lead vehicles.

A.1.3 Examples of Modeled Motion using EDR Data

This section includes four examples of vehicle motion models. To develop the models, we used EDR data and followed the approach in Section A.1.2. The models include three rear-end crashes: LVS, LVM, and LVD. The fourth model is from a straight-crossing path crash.

A.1.3.1 Stopped Lead Vehicle: Case 768013944

In this crash a constant-speed V1 struck a stopped V2. Table 11 presents speed data for this crash.

Table 11. Stopped Lead Vehicle EDR Speed Data

Time (sec)	V1 (mph)	V2 (mph)
-5	39	7
-4	39	4
-3	39	2
-2	38	0
-1	37	0

We modeled the striking vehicle as having a constant speed of 38.4 mph and the struck vehicle as being stopped. We calculated back in time from the crash and obtained the speeds and positions in Table 12. The speeds and positions enable us to calculate the range and range rate, which are included in the table.

Table 12. Stopped Lead Vehicle Modeled Pre-crash Data

Time	V1 accel (ft/sec^2)	V1 speed (ft/sec)	V1 pos (ft)	V2 accel (ft/sec^2)	V2 speed (ft/sec)	V2 pos (ft)	Range (ft)	Range rate (ft/sec)
-5	0	56.3	-281.5	0	0	0	281.5	-56.3
-4	0	56.3	-225.2	0	0	0	225.2	-56.3
-3	0	56.3	-168.9	0	0	0	168.9	-56.3
-2	0	56.3	-112.6	0	0	0	112.6	-56.3
-1	0	56.3	-56.3	0	0	0	56.3	-56.3
0	0	56.3	0	0	0	0	0	-56.3

A.1.3.2 Constant Speed Lead Vehicle: Case 769014578

In this crash a decelerating V1 struck a constant-speed V2. Table 13 presents speed data for this crash.

Table 13. Constant-Speed Lead Vehicle EDR Speed Data

Time (sec)	V1 (mph)	V2 (mph)
-5	78	11
-4	77	8
-3	76	8
-2	67	8
-1	50	9

We modeled the striking vehicle as having a constant deceleration from $t = -3$ seconds until the time of the crash at $t = 0$. The magnitude of the deceleration was:

$$\frac{(50 - 77)\frac{mile}{hour}}{2\ sec} \times 1.47\frac{\frac{ft}{sec}}{\frac{mile}{hour}} = -19.85\ ft/sec^2 \qquad (45)$$

where 77 mph is the average speed over -5 to -3 seconds (before the crash) and the speed changed from 77 to 50 mph takes place over 2 seconds. At the crash, the following vehicle had a speed of 53.4 ft/sec, obtained by applying the deceleration from -3 seconds to the crash. The lead vehicle was modeled as traveling at 8.8 mph, or 12.94 ft/sec. We calculated back in time from the crash and obtained the speeds, positions, range, and range rate values in Table 14.

Table 14. Constant-Speed Lead Vehicle Modeled Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (ft/sec)	V1 pos (ft)	V2 accel (ft/sec^2)	V2 speed (ft/sec)	V2 pos (ft)	Range (ft)	Range rate (ft/sec)
-5	0	112.9	-475.2	0.0	12.9	-64.7	410.5	-100.0
-4	0	112.9	-362.3	0.0	12.9	-51.8	310.5	-100.0
-3	-19.85	112.9	-249.4	0.0	12.9	-38.8	210.6	-100.0
-2	-19.85	93.1	-146.4	0.0	12.9	-25.9	120.5	-80.1
-1	-19.85	73.2	-63.3	0.0	12.9	-12.9	50.3	-60.3
0	-19.85	53.4	0.0	0.0	12.9	0.0	0.0	-40.4

A.1.3.3 Decelerating Lead Vehicle: Case 173007382

In this crash a constant-speed V1 struck a decelerating V2. Table 15 presents EDR speed data for this crash.

Table 15. Decelerating Lead Vehicle EDR Speed Data

Time (sec)	V1 (mph)	V2 (mph)
-5	35	37
-4	34	29
-3	34	20
-2	35	10
-1	37	3

We modeled the striking vehicle as having a constant speed of 35 mph (51.3 ft/sec) and the struck vehicle as decelerating from 37 mph to 0 mph over $t = -5$ seconds until the time of the crash at $t = 0$. The magnitude of the deceleration was:

$$\frac{(0 - 37)\frac{mile}{hour}}{5\ sec} \times 1.47\frac{\frac{ft}{sec}}{\frac{mile}{hour}} = -10.85\ ft/sec^2 \qquad (46)$$

We calculated back in time from the crash and obtained the speeds, positions, range, and range rate values in Table 16.

Table 16. Decelerating Lead Vehicle Modeled Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (ft/sec)	V1 pos (ft)	V2 accel (ft/sec^2)	V2 speed (ft/sec)	V2 pos (ft)	Range (ft)	Range rate (ft/sec)
-5	0	51.3	-256.5	-10.9	54.3	-135.6	120.9	3.0
-4	0	51.3	-205.2	-10.9	43.4	-86.8	118.4	-7.9
-3	0	51.3	-153.9	-10.9	32.6	-48.8	105.1	-18.8
-2	0	51.3	-102.6	-10.9	21.7	-21.7	80.9	-29.6
-1	0	51.3	-51.3	-10.9	10.9	-5.4	45.9	-40.5
0	0	51.3	0.0	-10.9	0.0	0.0	0.0	-51.3

A.1.3.4 Straight Crossing Path: Case 768014544

In this crash a southbound V1 entered an intersection, decelerating at a low rate. A westbound V2 traveling at 35 mph entered the intersection at the same time. V1 struck the right side of V2. Table 17 presents EDR speed data for this crash.

Table 17. Straight Crossing Path EDR Speed Data

Time (sec)	V1 (mph)	V2 (mph)
-5	36	38
-4	35	37
-3	34	36
-2	31	35
-1	28	35

We modeled the V1 as decelerating 6 mph over 2 seconds and continuing this deceleration up to the crash. In the crash, V1 struck V2 laterally, and focused on motion in V1's longitudinal axis and in V2's lateral axis. The magnitude of the V1's deceleration was:

$$\frac{(28-34)\frac{mile}{hour}}{2\ sec} \times 1.47\ \frac{\frac{ft}{sec}}{\frac{mile}{hour}} = -4.4\ ft/sec^2 \tag{47}$$

We calculated back in time from the crash and obtained the speeds, positions, range, and range rate values in Table 18. Although Table 18 includes kinematic data for V2, these values will not be used in subsequent momentum calculations in Section A.3.2.

Table 18. SCP Modeled Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (ft/sec)	V1 pos (ft)	V2 accel (ft/sec^2)	V2 speed (ft/sec)	V2 pos (ft)
-5	0.0	50.0	-230.2	0.0	51.4	-257.0
-4	0.0	50.0	-180.2	0.0	51.4	-205.6

Time	V1 accel (ft/sec^2)	V1 speed (ft/sec)	V1 pos (ft)	V2 accel (ft/sec^2)	V2 speed (ft/sec)	V2 pos (ft)
-3	-4.4	50.0	-130.2	0.0	51.4	-154.2
-2	-4.4	45.6	-82.4	0.0	51.4	-102.8
-1	-4.4	41.2	-39.0	0.0	51.4	-51.4
0	-4.4	36.8	0.0	0.0	51.4	0.0

A.2 Effect of Assumptions on Predictions

Implicit in Equations (42) and (43) is the assumption that the acceleration is applied at one of the EDR sampling times. Although this assumption simplifies the modeling of the motion, it is unlikely to be met in practice. Drivers will apply the brake or the accelerator whenever it suits them, and the EDR data will be stored when its accelerometers sense motion above some threshold. There is no reason for any change in acceleration to coincide with the EDR data sampling. Furthermore, because the EDR samples at a 1-second interval, we have a maximum 1-second uncertainty in our knowledge of when the acceleration changed. To illustrate: if the EDR sampled data at time $t = 0$, and the acceleration changed at $t = \delta$, we would not see the change in speed (which we use to estimate acceleration) until $t = 1$, the next sample period.

Since the EDR data is all we have to reconstruct the crash, we need to examine how uncertainty of the time the acceleration is applied influences the reconstruction. In particular, we need to analyze what sorts of speed and position errors this uncertainty introduces. For this analysis, it is simpler to work forward in time over a 2-second interval. Here the crash occurs at 2 seconds and the EDR begins recording at this time, saving data from 0 and 1 second. For the first case, we assume constant speed until the brake was applied at t_{appl}, sometime between 1 and 2 seconds, at which time the vehicle decelerated at a constant rate. Figure 29 shows the speed versus time plot for this conflict.
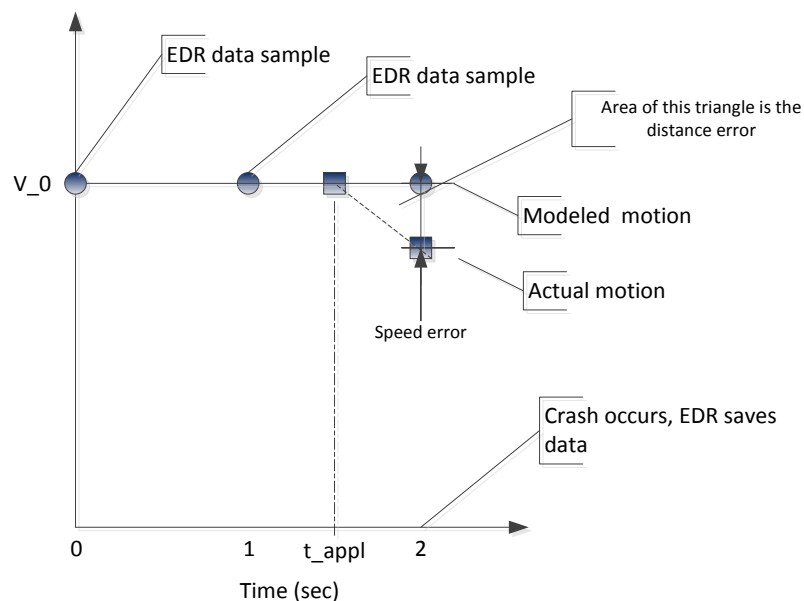

Figure 29. Error Analysis Geometry for Acceleration Change after Last Sample

Figure 29 shows the discrepancy between modeled and actual motion. Because the speed was constant at $t = 0$ and $t = 1$,[32] the speed model, Equation (42), assumes the speed is constant until the crash occurred. If, however, the driver braked and the vehicle started decelerating at some time between 1 and 2 seconds, it would be traveling at a slower speed when the crash occurred. It is a straightforward to determine the speed error:

$$\hat{v}_{error} = \Delta v_{actual} = (2 - t_{appl}) \times \ddot{x} \tag{48}$$

where $\hat{v}_{error}$ is the error in estimating the vehicle speed, v_{actual} is the actual vehicle speed, t_{appl} is the time the acceleration changes, and $\ddot{x}$ is the vehicle's acceleration from t_{appl} until the crash at $t = 2$.

In addition to the speed error in the modeled motion, there is also a distance error. The change in speed from t_{appl} to 2 seconds, which the model does not include, means the actual distance the vehicle traveled prior to the crash is shorter than the modeled distance. The distance error is:

$$\hat{d}_{error} = \frac{(2 - t_{appl})^2}{2} \times \ddot{x} \tag{49}$$

We consider one more case, the one in which the acceleration changes between 1 and 2 seconds prior to the crash. Figure 30 shows the geometry for estimating speed and range errors.
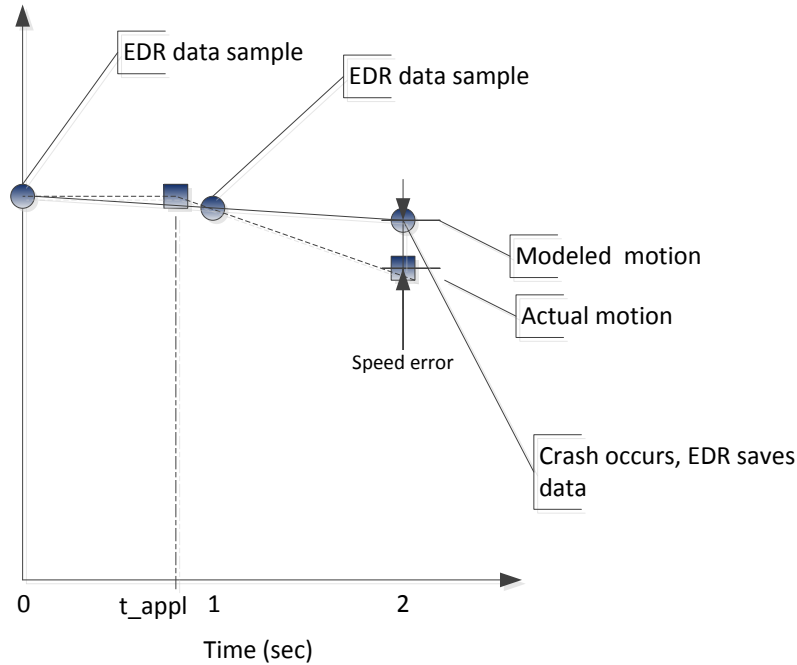
Figure 30. Error Analysis Geometry for Acceleration Change before Last Sample

The error analysis again examines speed and distance errors that result from sampling at times that differ from when the acceleration changes. The speed error in Figure 30 results from the difference in the modeled and actual speeds when the crash occurs. The actual speed equals:

$$v_{actual} = v_0 + (2 - t_{appl}) \times \ddot{x} \tag{50}$$

---

[32] These times would normally be t=-2 and t=-1.

The modeled speed results from estimating the acceleration between 0 and 1 second from the speed change and using this estimate to calculate the speed at 2 seconds:

$$v_{model} = v_0 + 2 \times (1 - t_{appl}) \times \ddot{x} \qquad (51)$$

The difference between the actual and the modeled speed is:

$$\hat{v}_{error} = v_{actual} - v_{model} = t_{appl} \times \ddot{x} \qquad (52)$$

Checking limit cases, if the acceleration changes at 0 seconds, there is no error in the speed estimate. If the acceleration changes at 1 second, the modeled speed error equals 1 (second) times the acceleration, which gives the same result as Equation (48). To analyze the modeled distance error, we calculate the area under the actual motion boundary in Figure 30 and subtract the area under the modeled motion boundary in the same figure. The resulting range error expression is:

$$\hat{d}_{error} = \frac{1}{2} t_{appl}^2 \times \ddot{x} \qquad (53)$$

Again checking limit cases, if the acceleration changes at 0 seconds, there is no error in the distance estimate. If the acceleration changes at 1 second, the modeled distance error equals 0.5 (second squared) times the acceleration, which gives the same result as Equation (49).
.

A.3 Changes in Speed (Delta V)

Using the modeled crash data and vehicle masses, this section applies conservation of momentum equations to determine post-crash speeds for the cases in Section A.1.3. The difference between pre- and post-crash speeds provides analytical ΔV values, which we compare with ΔV values in the crash database. The latter are obtained by measuring the deformation of a vehicle and relating this deformation to the kinetic energy expended in the crash. The rear-end crashes provide close agreement between "analytical" and measured ΔV. The SCP crash provides fair agreement, likely due to the more complicated crash dynamics and elastic behavior during the crash. The following is a series of cases studies identified and analyzed to validate the SIM tool.

A.3.1 Rear-End Collisions

A.3.1.1 Case 768013944 LVS

Case 768013944 involved V1 striking a stopped V2 with an impact speed of 56.5 ft/sec. We modeled the crash as inelastic and applied the conservation of linear momentum equation to determine the post-crash common speed of the two vehicles. The mass of vehicle 1 is 1,792 kg and that of vehicle 2 is 1,431 kg. Table 19 shows the post-crash speed and speed changes. The change in host (following vehicle) speed is close to the WinSmash result, 27.7 km/h versus 29 km/h, and the change in lead vehicle speed, 34.4 km/h versus 30 km/h, is also close to the WinSmash result.

Table 19. LVS Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (ft/sec)	31.3	31.3
V original (ft/sec)	56.5	0.0

Speed data	Vehicle 1	Vehicle 2
Delta V (km/h)	-27.7	34.4
Delta V WinSmash	-29.0	34.0
% Difference	4.4%	-1.3%

A.3.1.2 Case 769014578 LVM

Case 769014578 involved a decelerating V1 striking a constant-speed V2. We modeled the crash as inelastic and applied the conservation of linear momentum equation to determine the post-crash common speed of the two vehicles. The mass of V1 is 2,092 kg and that of V2 is 2,151 kg.

Table 20 shows the post-crash speed and speed changes. The change in host (following vehicle) speed is close to the WinSmash result, 22.5 km/h versus 22 km/h, and the change in lead vehicle speed, 22 km/h versus 20 km/h, is also close to the WinSmash result.

Table 20. LVM Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (ft/sec)	32.9	32.9
V original (ft/sec)	53.4	12.9
Delta V (km/h)	-22.5	22.0
Delta V WinSmash (km/h)	-22	20
% Difference	-2.3%	-9.8%

A.3.1.3 Case 173007382 LVD

In this crash a constant-speed V1 struck a decelerating V2. We modeled the striking vehicle as having a constant speed of 35 mph and the struck vehicle as decelerating to a stop. The masses of V1 and V2 are 2,126 and 1,563 kg. Modeling the crash as inelastic and applying the conservation of linear momentum equation to determine the post-crash common speed of the two vehicles, we obtained the post-crash results in Table 21.

Table 21. LVD Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (ft/sec)	29.6	29.6
V original (ft/sec)	51.5	0.0
Delta V (km/h)	-24.1	32.5
Delta V WinSmash (km/h)	-25.0	31.0
% Difference	3.6%	-5.0%

A.3.2 Straight-Crossing Paths

A.3.2.1 Straight-Crossing Paths - M Crash: Case 768014544

In this crash a decelerating southbound V1 entered an intersection and struck a westbound V2 traveling at 35 mph, with V1 striking the right side of V2. We modeled the southbound striking vehicle as having an impact speed of 25 mph and the westbound struck vehicle as having no speed in the struck (north-south) direction. The masses of V1 and V2 are 1,714kg and 1,507 kg. Modeling the crash as inelastic and

applying the conservation of linear momentum equation to determine the post-crash common speed of the two vehicles, we obtained the post-crash results in Table 22.

Table 22. SCP-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (ft/sec)	19.6	19.6
V original (ft/sec)	36.8	0.0
Delta V (km/h)	-18.9	21.5
Delta V WinSmash (km/h)	-17.0	18.0
% Difference	-11.3%	-19.6%

A.3.2.2 Straight-Crossing Path-S Crash: Case 777013658

V1 is host: accelerating vehicle.

Table 23. SCP-S Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	47	0	30	
-4	0	47	0	30	
-3	2.45	48	0	30	
-2	2.45	50	0	31	
-1	2.45	52	0	30	
0	2.45	53.67	0	30	48.4

The SIM calculates the range rate (or the crash speed) as the remote speed since the remote vehicle is the striking vehicle for the right-front collision mode. Thus, the range rate is calculated as the average speed of the remote V2. The average speed of V2 = 30 mph = 1.47 ft/sec/mph * 30 mph = 44.1 ft/sec = 1.09728 km/h/ft/sec * 44.1 ft/sec = 48.4 km/h. See Table 23.

The calculation of the acceleration of V1 is calculated similarly to Equation (106). Thus, acceleration of V1 = (52 - 47) mph/3 sec x 1.47 ft/sec/mph = 2.45 ft/sec^2. See Table 23.

V1 starts at 47 mph = 69.09 ft/sec and accelerates for 4 sec at 2.45 ft/sec^2 for a final impact speed of 78.89 ft/sec = 53.67 mph. See Table 23.

m_{HV} = 1804 kg and m_{RV} = 1601 kg so $1/\delta_{HV}$ = 1601/(1601+1804) = 0.470, $1/\delta_{RV}$ = 0.530. Then host Delta V = 48.4 /δ_{HV} = 22.75 km/h and similarly remote Delta V = 25.65 km/h.

The SIM input values are:
hostInitAccel = 2.45 ft/sec^2 x g/32.17 ft/sec^2 = 0.076 g.
remoteInitVel = 48.4 km/h
timeToIntersect = 5 sec
hostInitDistance = 90 m (calculated by estimation: 50 mph as an average speed)

SIM host Delta V = 22.76 km/h and SIM remote Delta V = 25.64 km/h. This gives essentially no error for host and remote. In addition, the total Delta V for vehicle 1 given by the WinSmash is 17 km/h which gives an error of 25 percent with the SIM value. The total delta V given by the WinSmash for vehicle 2 is 17 km/h. This gives an error of 34 percent with the SIM value. See Table 24.

Table 24. SCP-S Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	53.67	30
V initial (mph)	47	30
Delta V (km/h)	22.76	25.64
Delta V WinSmash	17	17
% Difference	25%	34%

A.3.2.3 Straight-Crossing Path -Acceleration Crash: Case 554017791

SCP: Stopped. Host: Accelerating-Remote:None

Table 25. SCP-S - Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	12	0	0	
-4.5	3.92	13	0	0	
-4	3.92	14	0	0	
-3.5	3.92	15	0	0	
-3	3.92	16	0	0	
-2.5	3.92	17	7.06	1	
-2	3.92	19	7.06	3	
-1.5	3.92	21	7.06	6	
-1	3.92	23	7.06	9	
-0.5	3.92	24	7.06	12	
0	3.92	25.37	7.06	14.45	40.85

Host is vehicle 2: collision is left-front.
V1 final speed is approximated as = range rate = 25.37 mph x 1.61 = 40.85 km/h.
Overall Acceleration of V2 = (12-0) mph/(5/2) sec x 1.47 ft/s/mph/32.17 = 0.22 g = 7.06 ft/sec^2.
V2 initial = 0 mph x 1.61 = 0 km/h.
V2 speed at impact = 7.06 ft/sec^2 x 3 sec = 21.18 ft/sec = 21.18 x 0.682 mph = 14.45 mph = 14.45 x 1.61 = 23.26 km/h = 23.2645/3.6 = 6.46 m/s. See Table 31.

m_{HV} = 1696 kg and m_{RV} = 1521 kg so $1/\delta_{HV}$ = 1521 /(1521 +1696) = 0.47 and $1/\delta_{RV}$ = 0.53. Then host Delta V = 40.85/δ_{HV} = 19.20 km/h and similarly remote Delta V = 21.65 km/h.

Distance Host Traveled: ½ x 7.06 x 3 x 3 = 31.77 ft x 0.3048 = 9.68 m.

SIM input values:
hostInitDist = 9.68 m
hostInitVel = 0 km/h
hostInitAccel = 0.22 g
hostFinalAccel = 0.22 g
remoteInitVel = 40.85 km/h
timeToIntersect = 3 sec

SIM output values: note that the SIM output has $1/\delta_{HV} = 0.47$ and $1/\delta_{RV} = 0.53$ and needs to be adjusted:
Host Delta V = 11.35 m/s x 3.6 = 40.86 km/h; 40.86 km/h x 0.47 = 19.20 km/h.
Remote Delta V = 11.35 m/s x 3.6 x 0.53 = 21.66 km/h.

The SIM output is: SIM host Delta V = 19.20 km/h and SIM remote Delta V = 21.66 km/h. This gives an error (with the above hand calculated values) for host of 0 percent and for remote of 0.03 percent.

The total Delta V for V1 given by WinSmash is 20 km/h which gives an error of 8 percent with the SIM value. The total Delta V given by WinSmash for V2 is 19 km/h. This gives an error of 1 percent with the SIM value. See Table 26.

Table 26. SCP-S Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	25.37	14.45
V initial (mph)	12	0
Delta V (km/h)	21.66	19.20
Delta V WinSmash (km/h)	20	19
% Difference	8%	1%

A.3.2.4 Straight-Crossing Path -Acceleration Crash: Case 771015220
SCP: Moving. Host:Accelerating-Remote:None

Table 27. SCP-M - Acceleration Pre-crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	30	0	26	
-4	0	30	2.94	26	
-3	0	31	2.94	27	
-2	0	32	2.94	29	
-1	0	34	2.94	32	
0	0	32	2.94	36.03	58.01

Host is vehicle 2: collision is front-left.

V1 initial is approx. by = 32 mph = 51.52 km/h

Overall Acceleration of V2 = (32-26) mph/(3) sec x 1.47 ft/s/mph/32.17 = 0.09 g = 2.94 ft/sec^2.

V2 initial = 26 mph x 1.61 = 41.86 km/h.

V2 speed at impact = 2.94 ft/sec^2 x 5 sec + 26 mph = 14.7 ft/sec + 26 mph = 14.7 x 0.682 mph + 26 mph = 10.03 mph +26 mph = 36.03 mph = 36.03 x 1.61 = 58.01 km/h = 58.01 /3.6 = 16.11 m/s. See Table 33.

m_{HV} = 1636 kg and m_{RV} = 1373 kg so $1/\delta_{HV}$ = 1373 /(1373 +1636) = 0.46 and $1/\delta_{RV}$ = 0.54. Then host Delta V = 58.01/δ_{HV} = 26.68 km/h and similarly remote Delta V = 31.33 km/h.

//Distance Host Traveled: 12 mph x h/3600 x 5 s x 5280 ft/mile + ½ x 3.92 x 5 x 5 = 137 ft x //0.3048 = 41.76 m.

SIM input values:

hostInitVel = 41.86 km/h

hostAccel = 0.09 g

remoteInitVel = 51.52 km/h

timeToIntersect = 5 sec

SIM output values: note that the SIM output has $1/\delta_{HV}$ = **0.46 and** $1/\delta_{RV}$ = 0.54 and needs to be adjusted:

Host Delta V = 14.46 m/s x 3.6 = 52.06 km/h; 52.06 km/h x 0.46 = 23.95 km/h.

Remote Delta V = 14.46 m/s x 3.6 x 0.54 = 28.11 km/h.

The SIM output is: SIM host Delta V = 23.95 km/h and SIM remote Delta V = 28.11 km/h. This gives an error (with the above hand calculated values) for host of 10 percent and for remote of 10 percent.

The total Delta V for V1 given by WinSmash is 39 km/h which gives an error of 28 percent with the SIM value. The total Delta V given by WinSmash for V2 is 18 km/h. This gives an error of 25 percent with the SIM value. See Table 28.

Table 28. SCP-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	32	36.03
V initial (mph)	32	26
Delta V (km/h)	28.11	23.95
Delta V WinSmash (km/h)	39	18
% Difference	28%	25%

A.3.2.5 Straight-Crossing Path -Acceleration Crash: Case 782013365

SCP: Stopped. Host:Accelerating-Remote:Braking

Table 29. SCP-S - Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	0		44	
-4	8.09	1		44	
-3	8.09	9		43	
-2	8.09	16		43	
-1	8.09	22	-24.99	26	
0	8.09	27.59	-24.99	8.91	44.41

Host is vehicle 1: collision is front-left.

Overall Acceleration of V1 = (22-0) mph/(4) sec x 1.47 ft/s/mph/32.17 = 0.25 g = 8.09 ft/sec^2.
V1 initial = 0 mph x 1.61 = 0 km/h.
V1 speed at impact = 8.09 ft/sec^2 x 5 sec = 40.45 ft/sec = 40.45 x 0.682 mph = 27.59 mph = 27.59 x 1.61
= 44.41 km/h = 44.41/3.6 = 12.34 m/s.

Initial Velocity of V2 = 44 mph x 1.61 = 70.84 km/h
Overall Deceleration of V2 = (43-26) mph/(1) sec x 1.47 ft/s/mph/32.17 = 0.78 g = 24.99 ft/sec^2.
V2 speed at impact => 24.99 ft/sec^2 x 2 sec = 49.98 ft/sec = 49.98 x 0.682 mph = 34.09 mph => 43 mph –
34.09 mph = 8.91 mph. 8.91 x 1.61 = 14.35 km/h = 14.35/3.6 = 3.99 m/s. See Table 35.

m_{HV} = 2336 kg and m_{RV} = 2336 kg so $1/\delta_{HV}$ = 2336 /(2336 +2336) = 0.5 and $1/\delta_{RV}$ = 0.5. Then host
Delta V = 44.41/δ_{HV} = 22.21 km/h and similarly remote Delta V = 22.21 km/h.

Distance Host Traveled: ½ x 8.09 x 5 x 5 = 101.13 ft x 0.3048 = 30.82 m.

SIM input values:
hostInitVel = 0 km/h
hostInitAccel = 0.25 g
hostReactionTime = 0 s
hostFinalAccel = 0.25 g
hostInitDist = 30.82 m
remoteReactionTime = 4 s
remoteDecel = 0.78 g
remoteInitVel = 70.84 km/h
timeToIntersect = 5 sec

SIM output values: note that the SIM output has $1/\delta_{HV}$ = 0.5 and $1/\delta_{RV}$ = 0.5 and needs to be adjusted:
Host Delta V = 12.31 m/s x 3.6 = 44.32 km/h; 44.32 km/h x 0.5 = 22.16 km/h.
Remote Delta V = 12.31 m/s x 3.6 x 0.5 = 22.16 km/h.

The SIM output is: SIM host Delta V = 22.16 km/h and SIM remote Delta V = 22.16 km/h. This gives an
error (with the above hand calculated values) for host of 0.2 percent and for remote of 0.2 percent.

The total Delta V for V1 given by WinSmash is 25 km/h which gives an error of 11.4 percent with the SIM value. The total Delta V given by WinSmash for V2 is 24 km/h. This gives an error of 7.7 percent with the SIM value. See Table 30.

Table 30. SCP-S Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	27.59	8.91
V initial (mph)	0	44
Delta V (km/h)	22.16	22.16
Delta V WinSmash (km/h)	25	24
% Difference	11.4%	7.7%

A.3.2.6 Straight-Crossing Path -Acceleration Crash: Case 834016755

SCP: Moving. Host:Accelerating-Remote:Braking

Table 31. SCP-M - Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5		18			
-4		14			
-3		14			
				70	
-2	6.62	19		70	
			-14.7	63	
-1	6.62	23	-14.7	57	
			-14.7	55	
0	6.62	27.54	-14.7	49.95	80.42

Host is vehicle 1: collision is right-front.

Overall Acceleration of V1 = (23-14) mph/(2) sec x 1.47 ft/s/mph/32.17 = 0.21 g = 6.62 ft/sec^2.
V1 initial = 14 mph x 1.61 = 22.54 km/h.
V1 speed at impact => 6.62 ft/sec^2 x 3 sec = 19.86 ft/sec = 19.86 x 0.682 mph = 13.54 mph. => 14 mph + 13.54 mph = 27.54 mph. 27.54 x 1.61 = 44.34 km/h = 44.34/3.6 = 12.32 m/s.
Initial Velocity of V2 = 70 mph x 1.61 = 112.70 km/h
Overall Deceleration of V2 = (70-55) mph/(3/2) sec x 1.47 ft/s/mph/32.17 = 0.46 g = 14.70 ft/sec^2.
V2 speed at impact => 14.7 ft/sec^2 x 4/2 sec = 29.4 ft/sec = 29.4 x 0.682 mph = 20.05 mph => 70 mph – 20.05 mph = 49.95 mph. 49.95 x 1.61 = 80.42 km/h = 80.42/3.6 = 22.34 m/s. See Table 37.

m_{HV} = 1891 kg and m_{RV} = 2393 kg so $1/\delta_{HV}$ = 2393 /(2393 +1891) = 0.56 and $1/\delta_{RV}$ = 0.44. Then host Delta V = 80.42/δ_{HV} = 45.04 km/h and similarly remote Delta V = 35.39 km/h.
//Distance Host Traveled: ½ x 8.09 x 5 x 5 = 101.13 ft x 0.3048 = 30.82 m.

SIM input values:
hostInitVel = 22.54 km/h
hostInitAccel = 0.21 g
hostReactionTime = 2 s
hostFinalAccel = 0.21 g
remoteReactionTime = 3 s
remoteDecel = 0.46 g
remoteInitVel = 70.84 km/h
timeToIntersect = 3 sec

SIM output values: note that the SIM output has $1/\delta_{HV}$ = 0.56 and $1/\delta_{RV}$ = 0.44 and needs to be adjusted:
Host Delta V = 19.68 m/s x 3.6 = 70.85 km/h; 70.85 km/h x 0.56 = 39.67 km/h.
Remote Delta V = 19.68 m/s x 3.6 x 0.44 = 31.17 km/h.

The SIM output is: SIM host Delta V = 39.67 km/h and SIM remote Delta V = 31.17 km/h. This gives an error (with the above hand calculated values) for host of 12 percent and for remote of 12 percent.

The total Delta V for V1 given by WinSmash is 63 km/h which gives an error of 37 percent with the SIM value. The total Delta V given by WinSmash for V2 is 49 km/h. This gives an error of 35 percent with the SIM value. See Table 32.

Table 32. SCP-S Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	27.54	49.95
V initial (mph)	14	70
Delta V (km/h)	39.67	31.17
Delta V WinSmash (km/h)	63	49
% Difference	37%	35%

A.3.2.7 Straight-Crossing Path -Acceleration Crash: Case *548019621*

SCP: Stopped. Host:Braking-Remote:Braking

Table 33. SCP-S - Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5		0		67	
				67	
-4	10.29	7		67	
				67	

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-3	10.29	14		68	
				68	
-2	-3.68	11		68	
				69	
-1	-3.68	9		69	
			-17.64	63	
0	-3.68	6.47	-17.64	56.97	91.72

Host is vehicle 1: collision is right-front.

Overall Acceleration of V1 = (14-0) mph/(2) sec x 1.47 ft/s/mph/32.17 = 0.32 g = 10.29 ft/sec^2.
V1 initial = 0 mph x 1.61 = 0 km/h.

Overall Deceleration of V1 = (14-9) mph/(2) sec x 1.47 ft/s/mph/32.17 = 0.11 g = 3.68 ft/sec^2.
V1 initial = 14 mph x 1.61 = 22.54 km/h = 22.54/3.6 = 6.26 m/s.
V1 speed at impact => 3.68 ft/sec^2 x 3 sec = 11.04 ft/sec = 11.04 x 0.682 mph = 7.53 mph => 14.00 -7.53 = 6.47 mph = 6.47 x 1.61 = 10.42 km/h = 10.42/3.6 = 2.89 m/s.

Initial Velocity of V2 = 67 mph x 1.61 = 107.87 km/h = 107.87/3.6 = 29.96 m/s.
Overall Deceleration of V2 = (69-63) mph/(1/2) sec x 1.47 ft/s/mph/32.17 = 0.55 g = 17.64 ft/sec^2.
V2 speed at impact => 17.64 ft/sec^2 x 1 sec = 17.64 ft/sec = 17.64 x 0.682 mph = 12.03 mph => 69 mph – 12.03 mph = 56.97 mph. 56.97 x 1.61 = 91.72 km/h = 91.72/3.6 = 25.48 m/s. See Table 39.

m_{HV} = 1221 kg and m_{RV} = 1340 kg so $1/\delta_{HV}$ = 1340 /(1340 +1221) = 0.48 and $1/\delta_{RV}$ = 0.52. Then host Delta V = 91.72/δ_{HV} = 44.03 km/h and similarly remote Delta V = 47.69 km/h.

Distance Host Traveled: ½ x 10.29 x 2 x 2 + 14 mph x 1h/3600s x 3s x 5280 ft/mile - ½ x 3.68 x 3 x 3 = (20.58+61.6-16.56) ft x 0.3048 = 20.0 m.

Note that since the HV did not start from zero the source code had to be modified for having an initial velocity.

SIM input values:
hostInitVel = 0 m/s
hostInitAccel = 0.32 g
hostReactionTime = 2 s
hostFinalAccel = 0.11 g
hostInitDist = 20.0 m
remoteReactionTime = 4 s
remoteDecel = 0.55 g
remoteInitVel = 107.87 km/h
timeToIntersect = 2 sec

SIM output values: note that the SIM output has $1/\delta_{HV}$ = 0.5 and $1/\delta_{RV}$ = 0.5 and needs to be adjusted:
Host Delta V = 24.03 m/s x 3.6 = 86.51 km/h; 86.51 km/h x 0.48 = 41.53 km/h.

Remote Delta V = 24.03 m/s x 3.6 x 0.52 = 44.98 km/h.

The SIM output is: SIM host Delta V = 41.53 km/h and SIM remote Delta V = 44.98 km/h. This gives an error (with the above hand calculated values) for host of 5.7 percent and for remote of 5.7 percent. The total Delta V for V1 given by WinSmash is 49 km/h which gives an error of 15 percent with the SIM value. The total Delta V given by WinSmash for V2 is 43 km/h. This gives an error of 4.4 percent with the SIM value. See Table 34.

Table 34. SCP-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	6.47	56.97
V initial (mph)	0	67
Delta V (km/h)	41.53	44.98
Delta V WinSmash (km/h)	49	43
% Difference	15%	4.4%

A.3.2.8 Straight-Crossing Path -Acceleration Crash: Case 552017517

SCP: Moving. Host:Braking-Remote:Braking

Table 35. SCP-M - Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5		24		N/A	
		24		N/A	
-4		24		N/A	
		24		N/A	
-3		24		N/A	
		24		38	
-2	-4.41	22		38	
	-4.41	19	-12.74	36	
-1	-4.41	19	-12.74	31	
	-4.41	18	-12.74	25	
0	-4.41	16.48	-12.74	20.62	33.20

Host is vehicle 2: collision is front-right.

Overall Deceleration of V1 = (24-18) mph/(4/2) sec x 1.47 ft/s/mph/32.17 = 0.14 g = 4.41 ft/sec^2.
V1 initial = 24 mph x 1.61 = 38.64 km/h.
V1 speed at impact => 4.41 ft/sec^2 x 5/2 sec = 11.03 ft/sec = 11.03 x 0.682 mph = 7.52 mph => 24.00 - 7.52 = 16.48 mph = 16.48 x 1.61 = 26.53 km/h.
Initial Velocity of V2 = 38 mph x 1.61 = 61.18 km/h.
Overall Deceleration of V2 = (38-25) mph/(3/2) sec x 1.47 ft/s/mph/32.17 = 0.40 g = 12.74 ft/sec^2.

V2 speed at impact => 12.74 ft/sec^2 x 4/2 sec = 25.48 ft/sec = 25.48 x 0.682 mph = 17.38 mph => 38 mph – 17.38 mph = 20.62 mph. 20.62 x 1.61 = 33.20 km/h. See Table 41.

m_{HV} = 1808 kg and m_{RV} = 2048 kg so $1/\delta_{HV}$ = 2048 /(2048 +1808) = 0.53 and $1/\delta_{RV}$ = 0.47. Then host Delta V = 33.20/δ_{HV} = 17.60 km/h and similarly remote Delta V = 15.60 km/h.

SIM input values:
hostInitVel = 61.18 km/h
hostReactionTime = 1 s
hostFinalAccel = 0.40 g
remoteReactionTime = 1 s
remoteDecel = 0.14 g
remoteInitVel = 38.64 km/h
timeToIntersect = 2.5 sec

SIM output values: note that the SIM output has $1/\delta_{HV}$ = 0.5 and $1/\delta_{RV}$ = 0.5 and needs to be adjusted:
Host Delta V = 9.42 m/s x 3.6 = 33.91 km/h; 33.91 km/h x 0.53 = 17.97 km/h.
Remote Delta V = 9.42 m/s x 3.6 x 0.47 = 15.94 km/h.

The SIM output is: SIM host Delta V = 17.97 km/h and SIM remote Delta V = 15.94 km/h. This gives an error (with the above hand calculated values) for host of 2 percent and for remote of 2 percent.

The total Delta V for V1 given by WinSmash is 13 km/h which gives an error of 18 percent with the SIM value. The total Delta V given by WinSmash for V2 is 11 km/h. This gives an error of percent with the SIM value. See Table 36.

Table 36. SCP-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	16.48	20.62
V initial (mph)	24	38
Delta V (km/h)	15.94	17.97
Delta V WinSmash (km/h)	13	11
% Difference	18%	38%

A.3.3 LTAP/OD

A.3.3.1 LTAP/OD-S Crash: Case 717016514

V2 is host.

Table 37. LTAP/OD-S Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	39		0?	
-4	0	39	4.41	3	

-3	0	40	4.41	6	
-2	0	40	4.41	10	
-1	0	41	4.41	12	
0	0	39.8	4.41	15.04	64.19

Average speed of V1 = 39.8 mph = 58.5 ft/sec = 64.19 km/h.

The calculation of the acceleration of V2 is calculated similarly to Equation (106). Thus, acceleration of V2 = (3 – 12) mph/3 sec x 1.47/32.17 = 4.41 ft/sec^2. See Table 37.
V2 speed at impact = 4.41 ft/sec^2 x 5 sec = 22.05 ft/sec = 15.04 mph. See Table 37.

The SIM calculates the range rate (or the crash speed) as the remote speed since the remote vehicle is the striking vehicle for the right-front collision mode. Thus the range rate is calculated as the average speed of the remote V1. Then host Delta V = 64.19 /δ_{HV} = 26.70 km/h and similarly remote Delta V = 37.49 km/h. In addition the host V2 orientation at collision is nearly perpendicular to the remote V1.

The SIM input values are:
hostInitAccel = 4.41 ft/sec^2 x g/32.17 ft/sec^2 = 0.137 g.
remoteInitVel = 64.2 km/h
timeToIntersect = 5 s
turnRadius = 8.5 m
m_{HV} = 2045 kg and m_{RV} = 1455 kg so 1/δ_{HV} = 1455/(1455+2045) = 0.416 and 1/δ_{RV} = 0.584.

The SIM output is: SIM host Delta V = 28.53 km/h and SIM remote Delta V = 40.09 km/h. This gives an error for host of 6.4 percent and for remote of 6.5 percent. In addition, the total Delta V for V1 given by WinSmash is 32 km/h which gives an error of 20 percent with the SIM value. The total Delta V given by WinSmash for V2 is 22 km/h. This gives an error of 23 percent with the SIM value. See Table 38.

Table 38. LTAP/OD-S Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	39.8	15.04
V initial (mph)	39	0
Delta V (km/h)	40.09	28.53
Delta V WinSmash	32	22
% Difference	20%	23%

A.3.3.2 LTAP/OD-M Crash: Case 769010829

V1 is host.

Table 39. LTAP/OD-M Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	6	0	50	
-4	4.04	7	0	50	
-3	4.04	10	0	49	
-2	4.04	13	0	49	
-1	4.04	17	0	48	
0	4.04	13.78	0	49.2	79.33

Average speed of V2 = 49.2 mph = 72.3 ft/sec = 79.33 km/h.

The calculation of the acceleration of V1 is calculated similarly to Equation (106). Thus, acceleration of V1 = (17-6) mph/4 sec x 1.47/32.17 = 0.126 g = 4.04 ft/sec². See Table 39.
V1 speed at impact = 4.04 ft/sec² x 5 sec = 20.2 ft/sec = 13.78 mph. See Table 39.

V1 initial speed = 6 mph x 1.47 x 1.0973 = 9.68 km/h.

The SIM calculates the range rate (or the crash speed) as the remote speed since the RV is the striking vehicle for the right-front collision mode. Thus the range rate is calculated as the average speed of the RV. The RV hit the right back of the host (i.e., not the front) when the host was mostly through its turn and essentially traveling perpendicular to the RV.

Then the range rate = 72.3 ft/sec x 1.0973 = 79.33 km/h.

m_{HV} = 1618 kg and m_{RV} = 2101 kg so $1/\delta_{HV}$ = 2101/(2101+1618) = 0.565 and $1/\delta_{RV}$ = 0.435. Then host Delta V = 79.33 /δ_{HV} = 44.82 km/h and similarly remote Delta V = 34.5 km/h.

The SIM input values are:
hostInitVel = 9.68 km/h
hostInitAccel = 0.126 g
remoteInitVel = 79.33 km/h
timeToIntersect = 5 sec
turnRadius = 8 m

The SIM output is: SIM host Delta V = 45.15 km/h and SIM remote Delta V = 34.77 km/h. This gives an error for host of 1 percent and for remote of 1 percent. In addition, the total Delta V for V1 given by WinSmash is 10 km/h which gives an error of 76 percent with the SIM value. The total Delta V given by WinSmash for V2 is 8 km/h. This gives an error of 75 percent with the SIM value.

Table 40. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	13.78	49.2
V initial (mph)	6	50
Delta V (km/h)	45.15	34.77

Delta V WinSmash	10	8
% Difference	76%	75%

A.3.3.3 LTAP/OD-Acceleration Crash: Case 773016111

Stopped Host:Accelerating-Remote:None

Table 41. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0	0	0	45	
-4.5	6.86	4	0	45	
-4	6.86	4	0	45	
-3.5	6.86	7	0	45	
-3	6.86	9	0	45	
-2.5	6.86	12	0	45	
-2	6.86	15	0	45	
-1.5	6.86	17	0	45	
-1	6.86	19	0	45	
-0.5	6.86	21	0	45	
0	6.86	23.39	0	45	72.45

Host is vehicle 1.
V2 final speed = range rate = 45 mph x 1.61 = 72.45 km/h.
Overall Acceleration of V1 = (21-0) mph/(9/2) sec x 1.47 ft/s/mph/32.17 = 0.21 g = 6.86 ft/sec^2.
Initial Acceleration of V1 = (7-0) mph/1.5 sec x 1.47/32.17 = 0.21 g = 6.86 ft/sec^2.
Final Acceleration of V1 = (21-7) mph/3 sec x 1.47/32.17 = 0.21 g = 6.86 ft/sec^2.
V1 initial = 0 km/h.
V1 speed at impact = 6.86 ft/sec^2 x 5 sec = 34.3 ft/sec = 34.3 x 0.682 mph = 23.39 mph. See Table 42.

m_{HV} = 1255 kg and m_{RV} = 1050 kg so $1/\delta_{HV}$ = 1050 /(1050 +1255) = 0.46 and $1/\delta_{RV}$ = 0.54. Then host Delta V = 72.45/δ_{HV} = 33.33 km/h and similarly remote Delta V = 39.12 km/h.

SIM input values:
hostInitVel = 0 km/h
hostInitAccel = 0.21g
hostFinalAccel = 0.21 g
remoteInitVel = 72.45 km/h
timeToIntersect = 5 sec
turnRadius = 15 m

SIM output values: note that the SIM output has $1/\delta_{HV}$ = $1/\delta_{RV}$ = 0.5. and needs to be adjusted:
Host Delta V = 20.13 m/s x 3.6 = 72.468 km/h; 72.468 km/h x 0.46 = 33.34 km/h.
Remote Delta V = 20.13 m/s x 3.6 x 0.54 = 39.13 km/h.

The SIM output is: SIM host Delta V = 33.34 km/h and SIM remote Delta V = 39.13 km/h. This gives an error (with the above hand calculated values) for host of 0.03 percent and for remote of 0.03 percent.

The total Delta V for V1 given by WinSmash is 33 km/h which gives an error of 1 percent with the SIM value. The total Delta V given by WinSmash for V2 is 37 km/h. This gives an error of 5.4 percent with the SIM value. See Table 42.

Table 42. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	23.39	45
V initial (mph)	0	45
Delta V (km/h)	33.34	39.13
Delta V WinSmash (km/h)	33	37
% Difference	1%	5.4%

A.3.3.4 LTAP/OD-Acceleration Crash: Case 768014946

Moving Host:Accelerating-Remote:None

Table 43. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	0		0		
-4.5			0		
-4			0		
-3.5			0		
-3	5.145		0		
-2.5	5.145	3	0	17	
-2	5.145	4	0	19	
-1.5	5.145	6	0	21	
-1	5.145	8	0	22	
-0.5	5.145	10	0	24	
0	5.145	12.28	0	21	33.81

Host is vehicle 1.
V2 final speed = range rate = 21 mph x 1.61 = 33.81 km/h.
Overall Acceleration of V1 = (10-3) mph/(4/2) sec x 1.47 ft/s/mph/32.17 = 0.16 g = 5.145 ft/sec^2.
V1 initial = 3 mph x 1.6 km/h /mph = 4.8 km/h.
V1 speed at impact = 5.145 ft/sec^2 x 3.5 sec = 18.0 ft/sec = 18 x 0.682 mph = 12.28 mph.

Distance Host Traveled: 3 mph x h/3600 x 2.5 x 5280 ft/mile + ½ x 5.145 x 2.5 x2.5 = 27 ft x 0.3048 = 8.25 m. See Table 44.

m_{HV} = 1627 kg and m_{RV} = 2416 kg so $1/\delta_{HV}$ = 2416 /(2416 +1627) = 0.6 and $1/\delta_{RV}$ = 0.4. Then host Delta V = 33.81/δ_{HV} = 20.29 km/h and similarly remote Delta V = 13.52 km/h.

SIM input values:
hostInitVel = 4.8 km/h
hostInitAccel = 0 g
hostReactionTime = 0.5 s
hostFinalAccel = 0.16 g
remoteInitVel = 33.81 km/h
timeToIntersect = 3 sec
turnRadius = 8.25 m

SIM output values: note that the SIM output has $1/\delta_{HV}$ = $1/\delta_{RV}$ = 0.5. and needs to be adjusted:
Host Delta V = 9.39 m/s x 3.6 = 33.80 km/h; 33.80 km/h x 0.6 = 20.28 km/h.
Remote Delta V = 9.39 m/s x 3.6 x 0.4 = 13.52 km/h.

The SIM output is: SIM host Delta V = 20.28 km/h and SIM remote Delta V = 13.52 km/h. This gives an error (with the above hand calculated values) of essentially 0 percent.

The total Delta V for V1 given by WinSmash is 26 km/h which gives an error of 22 percent with the SIM value. The total Delta V given by WinSmash for V2 is 20 km/h. This gives an error of 32.4 percent with the SIM value. See Table 44.

Table 44. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	12.28	21
V initial (mph)	3	21
Delta V (km/h)	20.28	13.52
Delta V WinSmash (km/h)	26	20
% Difference	22%	32.4%

A.3.3.5 LTAP/OD-Acceleration Crash: Case 688018443

Stopped Host:Accelerating-Remote:Braking

Table 45. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5			0		
-4.5			0		
-4			0		
-3.5			0		
-3		0	0		
-2.5	8.23	1	0	45	

-2	8.23	2	0	45	
-1.5	8.23	6	0	45	
-1	8.23	12	-20.58	44	
-0.5	8.23	14	-20.58	37	
0	8.23	16.84	-20.58	29.96	48.24

Host is vehicle 1.

Overall Deceleration of V2 = (44-37) mph/(0.5) sec x 1.47 ft/s/mph/32.17 = 0.64 g = 20.58 ft/sec^2.
V2 initial speed = 44 mph x 1.61 = 70.84 km/h.
V2 speed at impact => 20.58 ft/sec^2 x 1 sec = 20.58 ft/sec = 20.58 x 0.682 mph = 14.03 mph. So 44 mph
– 14.03 mph = 29.96 mph.
V2 final speed = range rate = 29.96 mph x 1.61 = 48.24 km/h.

Overall Acceleration of V1 = (14-0) mph/(5/2) sec x 1.47 ft/s/mph/32.17 = 0.26 g = 8.23 ft/sec^2.
V1 initial = 0 mph x 1.6 km/h /mph = 0 km/h.
V1 speed at impact = 8.23 ft/sec^2 x 3.0 sec = 24.69 ft/sec = 24.69 x 0.682 mph = 16.84 mph.

Distance Remote Traveled: 44 mph x h/3600 x 1 x 5280 ft/mile - ½ x 20.58 x 1 x 1 = (64.53-10.29) ft x
0.3048 = 16.53 m.

Distance Host Traveled: 0 mph x h/3600 x 3 x 5280 ft/mile + ½ x 8.23 x 3 x 3 = 37.04 ft x 0.3048 = 11.29
m.

Turn radius: r = 11.29/(3.14/2) = 7.19 m. See Table 51.

m_{HV} = 2307 kg and m_{RV} = 1864 kg so $1/\delta_{HV}$ = 1864 /(1864 +2307) = 0.45 and $1/\delta_{RV}$ = 0.55. Then host
Delta V = 48.24/δ_{HV} = 21.71 km/h and similarly remote Delta V = 26.53 km/h.

SIM input values:
hostInitVel = 0 km/h
hostInitAccel = 0.26 g
hostReactionTime = 0. s
hostFinalAccel = 0.26 g
remoteReactionTime = 1. s
remoteDecel = 0.64 g
remoteInitVel = 70.84 km/h
timeToIntersect = 2. sec
turnRadius = 7.19 m

SIM output values: note that the SIM output has $1/\delta_{HV}$ = $1/\delta_{RV}$ = 0.5. and needs to be adjusted:
Host Delta V = 10.83 m/s x 3.6 = 38.99 km/h; 38.99 km/h x 0.45 = 17.54 km/h.
Remote Delta V = 10.83 m/s x 3.6 x 0.55 = 21.44 km/h.

The SIM output is: SIM host Delta V = 17.54 km/h and SIM remote Delta V = 21.44 km/h. This gives an
error (with the above hand calculated values) of 19 percent for both host and remote.

The total Delta V for V1 given by WinSmash is 14 km/h which gives an error of 20 percent with the SIM value. The total Delta V given by WinSmash for V2 is 17 km/h. This gives an error of 20 percent with the SIM value. See Table 46.

Table 46. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	16.84	29.96
V initial (mph)	0	45
Delta V (km/h)	17.54	21.44
Delta V WinSmash (km/h)	14	17
% Difference	20%	20%

A.3.3.6 LTAP/OD-Acceleration Crash: Case 771014980

Moving Host:Accelerating-Remote:Braking

Table 47. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	2.94	9		45	
-4	2.94	12		47	
-3	2.94	14		48	
-2	2.94	16	-13.23	48	
-1	2.94	17	-13.23	39	
0	2.94	19.03	-13.23	29.95	48.22

Host is vehicle 1.

Overall Deceleration of V2 = (48-39) mph/(1) sec x 1.47 ft/s/mph/32.17 = 0.41 g = 13.23 ft/sec^2.
V2 initial speed = 48 mph x 1.61 = 77.28 km/h.
V2 speed at impact => 13.23 ft/sec^2 x 2 sec = 26.46 ft/sec = 26.46 x 0.682 mph = 18.05 mph. So 48 mph – 18.05 mph = 29.95 mph.
V2 final speed = range rate = 29.95 mph x 1.61 = 48.22 km/h.

Overall Acceleration of V1 = (17-9) mph/(4) sec x 1.47 ft/s/mph/32.17 = 0.09 g = 2.94 ft/sec^2.
V1 initial = 9 mph x 1.6 km/h /mph = 14.4 km/h.
V1 speed at impact => 2.94 ft/sec^2 x 5.0 sec = 14.7 ft/sec = 14.7 x 0.682 mph = 10.03 mph. So speed at impact is 9 mph + 10.03 mph = 19.03 mph.

Distance Remote Traveled: 48 mph x h/3600 x 2 x 5280 ft/mile - ½ x 13.23 x 2 x 2 = (140.8 - 26.46) ft x 0.3048 = 34.85 m. See Table 53.

Distance Host Traveled: 9 mph x 1h/3600s x 5s x 5280 ft/mile + ½ x 2.94 x 6 x 6 = (66 + 52.92) ft x 0.3048 = 36.25 m.
Turn radius: r = 36.25/(3.14/2) = 23.08 m.

m_{HV} = 1431 kg and m_{RV} = 1431 kg so $1/\delta_{HV}$ = 1431 /(1431 +1431) = 0.5 and $1/\delta_{RV}$ = 0.5. Then host Delta V = 48.22/δ_{HV} = 24.11 km/h and similarly remote Delta V = 24.11 km/h.

SIM input values:
hostInitVel = 14.4 km/h
hostInitAccel = 0. g
hostReactionTime = 0. s
hostFinalAccel = 0.09 g
remoteReactionTime = 2. s
remoteDecel = 0.41 g
remoteInitVel = 77.28 km/h
timeToIntersect = 3.6 s
turnRadius = 23.08 m

SIM output values: note that the SIM output has $1/\delta_{HV}$ = $1/\delta_{RV}$ = 0.5. and needs to be adjusted:
Host Delta V = 13.59 m/s x 3.6 = 48.92 km/h; 48.92 km/h x 0.5 = 24.46 km/h.
Remote Delta V = 13.59 m/s x 3.6 x 0.5 = 24.46 km/h.

The SIM output is: SIM host Delta V = 24.46 km/h and SIM remote Delta V = 24.46 km/h. This gives an error (with the above hand calculated values) of 1.4 percent.

The total Delta V for V1 given by WinSmash is 20 km/h which gives an error of 18 percent with the SIM value. The total Delta V given by WinSmash for V2 is 17 km/h. This gives an error of 30 percent with the SIM value. See Table 48.

Table 48. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	19.03	29.95
V initial (mph)	9	48
Delta V (km/h)	24.46	24.46
Delta V WinSmash (km/h)	20	17
% Difference	18%	30%

A.3.3.7 LTAP/OD-Acceleration Crash: Case 834016995

Stopped Host:Brake-Remote:Brake

Table 49. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	4.41	3		37	
-4	4.41	2		37	
-3	4.41	6		36	
-2	4.41	12		35	
-1	-13.23	3	-45.57	4	
0	-13.23	0	-45.57	0	0

Host is vehicle 1.

Overall Deceleration of V2 = (35-4) mph/(1) sec x 1.47 ft/s/mph/32.17 = 1.42 g = 45.57 ft/sec^2.
V2 initial speed = 35 mph x 1.61 = 56.35 km/h.
V2 speed at impact => 45.57 ft/sec^2 x 2 sec = 91.14 ft/sec = 91.14 x 0.682 mph = 62.16 mph. So 35 mph – 62.16 mph = -27.16 mph. so V2 comes to a stop.
V2 final speed = range rate = 0 mph x 1.61 = 0 km/h.

Initial Acceleration of V1 = (12-3) mph/(3) sec x 1.47 ft/s/mph/32.17 = 0.14 g = 4.41 ft/sec^2.
V1 initial = N/A mph x 1.6 km/h /mph = N/A km/h.
Deceleration of V1 = (12-3) mph/(1) sec x 1.47 ft/s/mph/32.17 = 0.41 g = 13.23 ft/sec^2.
V1 speed at impact => 13.23 ft/sec^2 x 2.0 sec = 26.46 ft/sec = 26.46 x 0.682 mph = 18.05 mph. So speed at impact is 12 mph – 18.05 mph = -6.05 mph. so V1 comes to a stop.

Stopping distance for host => v = 12 mph x 1.47 = 17.64 ft/s.
Distance Host Traveled: 0 mph x 1h/3600s x 3s x 5280 ft/mile + ½ x 4.41 x 3 x 3 + 17.64 x 17.64 / (2x13.23) = (0+19.85+ 11.76) ft x 0.3048 = 9.63 m.

Turn radius: r = 9.63/(3.14/2) = 6.14 m. See Table 55.

m_{HV} = 1384 kg and m_{RV} = 1490 kg so 1/δ_{HV} = 1490 /(1490 +1384) = 0.52 and 1/δ_{RV} = 0.48. Then host Delta V = 0/δ_{HV} = 0 km/h and similarly remote Delta V = 0 km/h.

SIM input values:
hostInitVel = 0 km/h
hostInitAccel = 0.14 g
hostReactionTime = 3. s
hostFinalAccel = -0.41 g
remoteReactionTime = 3. s
remoteDecel = 1.42 g
remoteInitVel = 56.35 km/h
timeToIntersect = 2.5 s
turnRadius = 6.14 m

SIM output values: note that the SIM output has 1/δ_{HV} = 0.52 and 1/δ_{RV} = 0.48 and needs to be adjusted:
Host Delta V = 15.65 m/s x 3.6 = 56.34 km/h; 56.34 km/h x 0.52 = 29.30 km/h.
Remote Delta V = 15.65 m/s x 3.6 x 0.48 = 27.04 km/h.

The SIM output is: SIM host Delta V = 29.30 km/h and SIM remote Delta V = 27.04 km/h. This gives an error (with the above hand calculated values) of 100 percent. This is due to our definition of Delta V using the range rate.

The total Delta V for V1 given by WinSmash is 33 km/h which gives an error of 11 percent with the SIM value. The total Delta V given by WinSmash for V2 is 31 km/h. This gives an error of 13 percent with the SIM value. See Table 50.

Table 50. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	0	0
V initial (mph)	0	35
Delta V (km/h)	29.30	27.04
Delta V WinSmash (km/h)	33	31
% Difference	11%	13%

A.3.3.8 LTAP/OD-Acceleration Crash: Case 768012367

Moving Brake-Brake

Table 51. LTAP/OD-Acceleration Pre-Crash Data

Time	V1 accel (ft/sec^2)	V1 speed (mph)	V2 accel (ft/sec^2)	V2 speed (mph)	Range rate (km/h)
-5	3.43	9		46	
-4	3.43	11		45	
-3	3.43	13		44	
-2	3.43	16	-16.91	37	
-1	-7.35	11	-16.91	21	
0	-7.35	5.97	-16.91	9.4	15.13

Host is vehicle 1.

Overall Deceleration of V2 = (44-21) mph/(2) sec x 1.47 ft/s/mph/32.17 = 0.53 g = 16.91 ft/sec^2.
V2 initial speed = 44 mph x 1.61 = 70.84 km/h.
V2 speed at impact => 16.91 ft/sec^2 x 3 sec = 50.73 ft/sec = 50.73 x 0.682 mph = 34.60 mph. So 44 mph – 34.60 mph = 9.4 mph.
V2 final speed = range rate = 9.4 mph x 1.61 = 15.13 km/h.

Initial Acceleration of V1 = (16-9) mph/(3) sec x 1.47 ft/s/mph/32.17 = 0.11 g = 3.43 ft/sec^2.
V1 initial = 9 mph x 1.61 km/h /mph = 14.49 km/h.
Deceleration of V1 = (16-11) mph/(1) sec x 1.47 ft/s/mph/32.17 = 0.23 g = 7.35 ft/sec^2.
V1 speed at impact => 7.35 ft/sec^2 x 2.0 sec = 14.70 ft/sec = 14.70 x 0.682 mph = 10.03 mph. So speed at impact is 16 mph – 10.03 mph = 5.97 mph.

Distance Host Traveled: 9 mph x 1h/3600s x 3s x 5280 ft/mile + ½ x 3.43 x 3 x 3 + 5 mph x1h/3600 x 2s x 5280 ft/mile = (54.27 + 15.44) ft x 0.3048 = 21.25 m.

Turn radius: r = 21.25/(3.14/2) = 13.53 m. See Table 57.

m_{HV} = 1552 kg and m_{RV} = 1750 kg so $1/\delta_{HV}$ = 1750 /(1750 +1552) = 0.53 and $1/\delta_{RV}$ = 0.47. Then host Delta V = 15.13/δ_{HV} = 8.02 km/h and similarly remote Delta V = 7.11 km/h.

SIM input values:
hostInitVel = 14.49 km/h
hostInitAccel = 0. g
hostReactionTime = 3. s
hostFinalAccel = -0.23 g
remoteReactionTime = 2. s
remoteDecel = 0.53 g
remoteInitVel = 70.84 km/h
timeToIntersect = 3.7 s
turnRadius = 13.53 m

SIM output values: note that the SIM output has $1/\delta_{HV}$ = 0.53 and $1/\delta_{RV}$ = 0.47 and needs to be adjusted:
Host Delta V = 4.55 m/s x 3.6 = 16.38 km/h; 16.38 km/h x 0.53 = 8.68 km/h.
Remote Delta V = 4.55 m/s x 3.6 x 0.47 = 7.70 km/h.

The SIM output is: SIM host Delta V = 8.68 km/h and SIM remote Delta V = 7.70 km/h. This gives an error (with the above hand calculated values) of 7.6 percent for both.

The total Delta V for V1 given by WinSmash is not provided. The total Delta V given by WinSmash for V2 is also not provided. See Table 52.

Table 52. LTAP/OD-M Pre- and Post-Crash Speed Data

Speed data	Vehicle 1	Vehicle 2
V final (mph)	5.97	9.4
V initial (mph)	9	44
Delta V (km/h)	8.68	7.70
Delta V WinSmash (km/h)	unknown	unknown
% Difference	N/A	N/A

A.3.4 Lane Change

A.3.4.1 Lane Change Crash: Case 773016952

V1 is host.

V1 is taken as average of EDR: = 51.6 mph = 83.23 km/h. V2 is a constant 75 mph = 120.98 km/h. The angle between the two vehicles is approximately 20 degrees. The total mass is m_T. The masses are m_{HV} = 1239 kg and m_{RV} =2275 kg. Then m_{HV} /m_T = $1/\delta_{RV}$ = 0.353 and m_{RV}/m_T = $1/\delta_{HV}$ = 0.647.

For determining the host Delta V and remote Delta V we use the following method: Find host Delta V using Equation (54),

$$host\ Delta\ V = \frac{|V_{HV} - V_{RV}|}{\delta_{HV}}$$

(54)

and similarly the remote Delta V = $|V_{HV} - V_{RV}| / \delta_{RV}$ where V_{HV} and V_{RV} are two dimensional vectors.

Thus, using Equation (54) host Delta V is = Sqrt((83.23 x sin(20))^2) + (83.23 x cos(20) - 120.98)^2)) x 0.647 = 33.24 km/h. A similar result for remote Delta V = 18.14 km/h.

The SIM inputs are:
hostVehicleLongitudinalVelocity = 83.23 x cos(20) = 78.21 km/h
hostAlertLateralSpeed = 83.23 x sin(20)/3.6 = 7.81 m/sec
hostAlertLateralAccel = 20 g
hostAlertLateralJerk = 10 g/sec
remoteVehicleLongitudinalVelocity = 120.98 km/h
remoteDistancetoLaneMarker = 1 m

The SIM output is: SIM host Delta V = 33.36 km/h and SIM remote Delta V = 18.17 km/h which are essentially equal to the hand calculated values. The values agree reasonably well with the WinSmash Delta V's: host Delta V = 25 km/h and remote Delta V = 14 km/h. These give errors of 25 percent and 23 percent respectively with the SIM results. See Table 53. The reason for the reasonable results may be that there was no rotational motion after the collision and the vehicles moved away essentially with the same speed.

Table 53. Lane Change Delta V

Speed data	Vehicle 1	Vehicle 2
Delta V (km/h)	33.36	18.17
Delta V WinSmash	25	14
% Difference	25%	23%

A.3.5 OD/No-Maneuver

A.3.5.1 OD/No-Maneuver Crash: Case 768015403

V1 is host.

V1, the host impact velocity, is approximately 32 mph = 51.6 km/h. V2, the remote impact velocity, is approximately 38 mph = 61.3 km/h. The angle between the two vehicles is about 10 degrees. The masses are m_{HV} = 1572 kg and m_{RV} = 1749 kg. Then $1/\delta_{RV}$ = 0.473 and $1/\delta_{HV}$ = 0.527.

Then since the collision is front-front,

$$host\ Delta\ V = \frac{(V1\ cos(theta) + V2)}{\delta_{HV}}$$

(55)

Then the host Delta V = (51.6 x cos(10) + 61.3) x 0.527 = 112.12 x 0.527 = 59.09 km/h. A similar result for remote Delta V = 53.03 km/h.

The SIM inputs are:
hostVehicleLongitudinalVelocity = 51.6 x cos(10) = 50.82 km/h
hostAlertLateralSpeed = 51.6 x sin(10)/3.6 = 2.49 m/sec
hostAlertLateralAccel = 0 g
hostAlertLateralJerk = 0 g/sec
remoteVehicleLongitudinalVelocity = 61.3 km/h
remoteDistancetoLaneMarker = 1 m
hostDistancetoLaneMarker = 1 m
remoteLongitudinalDistance = 61.3 km/h / 3.6 x 5 sec = 85.14 m

The SIM output is: SIM host Delta V SIM = 59.05 km/h and SIM remote Delta V = 53.07 km/h which are essentially equal to the above hand calculated values. The values agree reasonably well with WinSmash Delta V's: host Delta V = 69 km/h and remote Delta V = 61 km/h. These give errors of 14.4 percent and 13 percent respectively. See Table 54. The collision was almost inelastic (the vehicles nearly traveled as a unit after the collision and did not travel far).

Table 54. OD/No Man Delta V

Speed data	Vehicle 1	Vehicle 2
Delta V (km/h)	59.05	53.07
Delta V WinSmash	69	61
% Difference	14.4%	13%

A.3.6 DNPW OD/Maneuver

A.3.6.1 DNPW OD/Maneuver Crash: Case 831016799

V1 is host: use WinSmash Delta V to estimate V2.

V1, the host impact velocity, is approximately 48 mph = 77.43 km/h. V2 is solved using Delta V (below). The angle between the two vehicles is 10 degrees. The masses are m_{HV} = 1225 kg and m_{RV} = 1105 kg. Then $1/\delta_{RV}$ = 0.526 and $1/\delta_{HV}$ = 0.474.

The Delta V is taken from the NASS data and used to find V2: host Delta V = 38 km/h. Then since the collision is front-front use Equation (55) to get host Delta V = (77.43 x cos(10) + V2) /δ_{HV} = (75.1 + V2) x 0.474 = 38 km/h. Then solve this equation for V2 = 38/0.474 – 75.1 = 5.07 km/h.

Determine the SIM input variable betaInitialRemote1YDistance: V1 = 48 mph x 1.47 ft/sec/mph = 70.56 ft/sec. Then betaInitialRemote1YDistance = 70.56 ft/sec x 4 sec = 282.24 ft = 94 m.

Determine the SIM input variable betaInitialRemoteYDistance:
V2 = 5.07 km/h / 1.0973 km/h/ft/sec = 4.62 ft/sec.
So betaInitialRemoteYDistance = 4.62 ft/sec x 4 sec + betaInitialRemote1YDistance =100.16 m.

The SIM inputs are:
betaDriverJerk_base = 20 g/sec
betaDriverJerk_treat = 40 g/sec
betaHostLongVel = 77.43 km/h
betaBaselineHostAccel = 0.0 g

betatreat1HostAccel = 0.8 g
remoteDistancetoLaneMarker = 1 m
hostDistancetoLaneMarker = 0 m
betaInitialRemote1YDistance = 94 m
betaInitialRemoteYDistance = 100.16 m
betaRemote1VehicleLongitudinalVelocity = 0 km/h
betaRemoteVehicleLongitudinalVelocity = 5.07 km/h

The SIM output is: SIM host Delta V = 41.25 km/h. The values agree well with the WinSmash host Delta V = 38 km/h. This gives an error of 7.9 percent. See Table 55. Thus the Delta V calculation is seen to be consistent. The collision was essentially inelastic and the vehicles were quite close after the collision.

Table 55. DNPW OD/Man Delta V

Speed data	Vehicle 1
Delta V (km/h)	41.25
Delta V WinSmash	38
% Difference	7.9%

A.3.6.2 DNPW OD/Maneuver Crash: Case 511015297

V1 is host: Use speed limit to estimate V2.

Speed Limit = 40 km/h. V1, the host impact velocity, is taken to be approximately = 36 mph = 58.07 km/h. V2 is estimated as the speed limit = 40 km/h. The angle between the two vehicles is 10 degrees. The masses are m_{HV} = 1850 kg and m_{RV} = 2419 kg. Then $1/\delta_{RV}$ = 0.433 and $1/\delta_{HV}$ = 0.567.

Then since the collision is front-front Equation **(55)** can be used to obtain host Delta V = (58.07 x cos(10) + 40) x 0.567 = 49 km/h.

Determine the SIM input variable betaInitialRemote1YDistance: V1 = 36 mph x 1.47 ft/sec/mph = 52.92 ft/sec. Then betaInitialRemote1YDistance = 52.92 ft/sec x 5 sec = 264.6 ft = 88.2 m.

Determine the SIM input variable betaInitialRemoteYDistance:
V2 = 40 km/h / 1.0973 km/h/ft/sec = 36.45 ft/sec.
So betaInitialRemoteYDistance = 36.45 ft/sec x 5 sec + betaInitialRemote1YDistance =149 m.

The SIM inputs are:
betaDriverJerk_base = 20 g/sec
betaDriverJerk_treat = 40 g/sec
betaHostLongVel = 58.07 km/h
betaBaselineHostAccel = 0.0 g
betatreat1HostAccel = 0.8 g
remoteDistancetoLaneMarker = 1 m
hostDistancetoLaneMarker = 0 m
betaInitialRemote1YDistance = 88.2 m
betaInitialRemoteYDistance = 149 m
betaRemote1VehicleLongitudinalVelocity = 0 km/h
betaRemoteVehicleLongitudinalVelocity = 40 km/h

The SIM output is: SIM host Delta V = 49.04 km/h. We note that the hand calculated Delta V = 49 and this agrees exactly with host Delta V SIM. The WinSmash host Delta V = 37 km/h. This gives an error of 25 percent. See Table 56. There is reasonably good agreement and the collision was essentially inelastic and the vehicles were quite close after the collision.

Table 56. DNPW OD/Man Delta V

Speed data	Vehicle 1
Delta V (km/h)	49.04
Delta V WinSmash	37
% Difference	25%

A.3.7 Comment on Results

Involving the front of one vehicle impacting the rear of another, rear-end crashes have straight-forward crash dynamics (forces and motion). Each vehicle has a crumple zone (the front of the striking vehicle and the rear of the struck vehicle) that absorbs the energy expended in the crash. Furthermore, with both vehicles moving in the same direction and in the same lane, many rear-end crashes produce little rotational motion as a byproduct. Therefore, the conservation of linear momentum can be applied to determine the post-crash speed. The combination of crumple zones and same-axis motion, along with the close agreement between estimated ΔV and WinSmash ΔV in Table 19, Table 20, and Table 21 suggests the following holds for these rear-end crashes:

- The crumple zones absorbed the impact energy, allowing the striking and struck vehicles to have a common velocity after the crash
- Assuming and applying the conservation of linear momentum predicted the post-crash speed reasonably well

Involving the front of one vehicle impacting the side of another, SCP crashes tend to have more complex crash dynamics than rear-end crashes. Only the striking vehicle has an extended crumple zone available to absorb the energy expended in the crash. The struck vehicle has a much shorter crumple zone (the vehicle side) to absorb crash energy. In addition, with the vehicles moving in orthogonal directions (90 degree angle), many SCP crashes produce rotational motion as a byproduct. Rotational motion invalidates the conservation of linear momentum, so it cannot be applied to determine the post-crash speed. Although the CDS crash database includes many SCP crashes with little rotational motion, the lack of a long crumple zone on the struck vehicles means that the two vehicles may not have a common speed (in the struck axis) after the crash. That is, the collision may have an elastic component and the vehicles will separate after the initial impact, in effect bouncing apart. The combination of rotational motion and insufficient crumple zone on the struck vehicle complicate post-crash motion and help explain the discrepancy between WinSmash ΔV results and analytical results in Table 22, Table 24, and Table 38. The combination of significant rotational and translational motion, considerably large post-crash positioning, and lack of crumple zone on the struck vehicle backend may help explain the large discrepancy between SIM ΔV results and WinSmash results in Table 40. For the lane change conflict, the side-side collision is essentially elastic with no crumple zones and this may help explain the results discrepancy given in Table 53. In the second instance of the DNPW OD/Maneuver conflict, the result discrepancy shown in Table 56 may be partly due to the need to estimate one of the vehicles' velocity by using the posted speed limit.

Appendix B: Closed-Form Implementation of Kinematic Modules

Currently, the SIM tool implements three modules (rear-end, crossing paths, and lane change) in a closed-form (CF) solution, in addition to the time-step iterative process described above in this report. The CF solution works differently from the stepwise numerical modules that evaluate all kinematic variables at each step within a given run. The CF solution computes the impact speed and the *ΔV* values for each run using a set of equations that interpret the inputs and calculate the outcome in one algorithmic step. This step applies the same governing equations from Section 3.2. There are conditions in the CF code that first determine whether a crash has occurred; in case of a crash, the CF equations are applied and results displayed.

These CF solutions may process faster and interpret kinematics at a higher resolution (i.e., not relegated to a 0.1 second resolution, and can be solved to any placeholder); however, they are not as flexible and are employed only in ideal conflicts.

B.1 Rear-End Closed-Form Module

The rear-end CF solution can be applied to LVS, LVM, and LVD conflicts, only when the HV's attempted avoidance maneuver is to brake. The manner in which each set of CF methods are derived are described below. .

B.1.1 LVS - Host Braking

The CF solution for the LVS conflict is derived in the following manner:

1. Since the acceleration (i.e., braking) of the HV is constant, the velocity is linear and a decreasing function of time (see Figure 31). Equation (56) gives the velocity, v:

$$v_c = -a_{HVLon}t + v_{HVLon} \qquad (56)$$

From 0 to t_R, the speed is v_{HV}. At time v_{HV}/a_{HV}, the HV has come to a stop. At the collision time t_C, the collision speed is v_C.
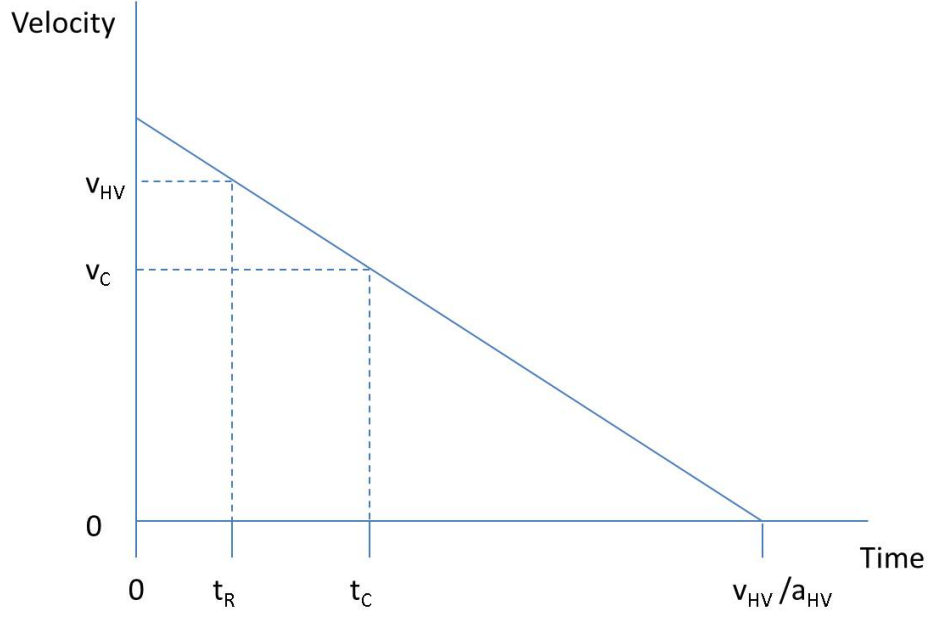
Figure 31. LVS Velocity

2. Since the velocity is linear, the distance traveled is a quadratic function of time (see Figure 32). Equation (57) gives the parabolic form of the distance, d:

$$d = -\frac{1}{2} a_{HV}\, t^2 + v_{HV} t + v_{HV} t_R \tag{57}$$

By completing the square, this can be rewritten as Equation (58):

$$d_H = -\frac{1}{2} a_{HV} \left(t - \frac{v_{HV}}{a_{HV}} \right)^2 + \frac{1}{2} \frac{v_{HV}{}^2}{a_{HV}} + v_{HV} t_R \tag{58}$$

The distance traveled to come to a stop at $t = \frac{v_H}{a_H}$ is the distance $d = \frac{1}{2} \frac{v_H{}^2}{a_H} + v_H t_R$ as expected.

The distance R_0 is the initial separation of the HV and RV. Then, the time of collision, $t = t_C$ in Equation (58) is given when the condition $d_H = R_0$ is satisfied. In this case, t_C is given by Equation (59):

$$t_C = \pm \sqrt{\frac{2}{a_{HV}} \left(\frac{1}{2} \frac{v_{HV}^2}{a_{HV}} + v_{HV} t_R - R_0 \right)} + \frac{v_{HV}}{a_{HV}} \tag{59}$$

Substituting Equation (59) into Equation **(55)** gives Equation (60), the *LVS collision velocity*:

$$v_C = \sqrt{2 a_{HV} \left(\frac{1}{2} \frac{v_{HV}^2}{a_{HV}} + v_{HV} t_R - R_0 \right)} \tag{60}$$

B-2

Distance

$\frac{1}{2}\frac{v_{HV}^2}{a_{HV}} + v_{HV}t_R$ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄

R_0 ┄┄┄┄┄┄┄┄┄┄┄

$v_{HV}\,t_R$ ┄┄┄┄┄

0

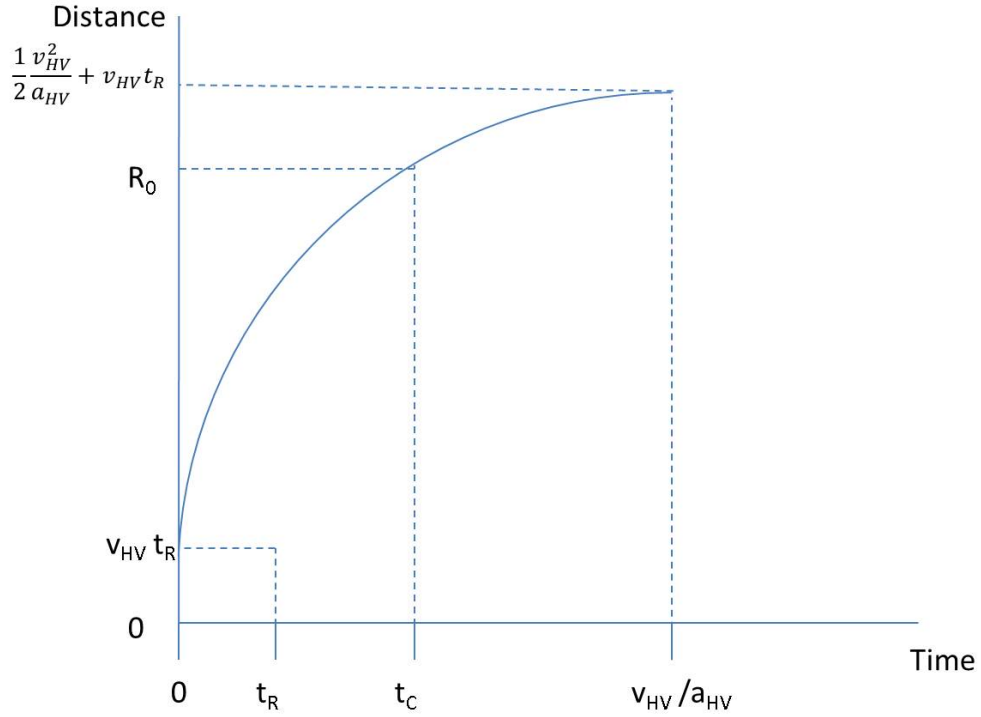   0 t_R t_C v_{HV}/a_{HV} Time

Figure 32. LVS Collision Distance Versus Time

B.1.2 LVM Collision Velocity

The CF equation for the LVM collision velocity is derived in a similar manner as the LVS equation. The collision velocity is given by Equation (61):

$$v_C = v_1 - v_2 \tag{61}$$

where the RV velocity is constant and the HV velocity is as in Equation (62):

$$v_2 = v_{RV} \quad \text{and} \quad v_1 = -a_{HV}t_C + v_{HV} \tag{62}$$

Since the RV velocity is constant, the distance traveled for the RV is a linear function of time:

$$d_R = v_{RV}t + R_0 \tag{63}$$

The distance behavior for the HV is again given by Figure 33. The intersection of the two curves defines the collision time, t_C (see Figure 34).
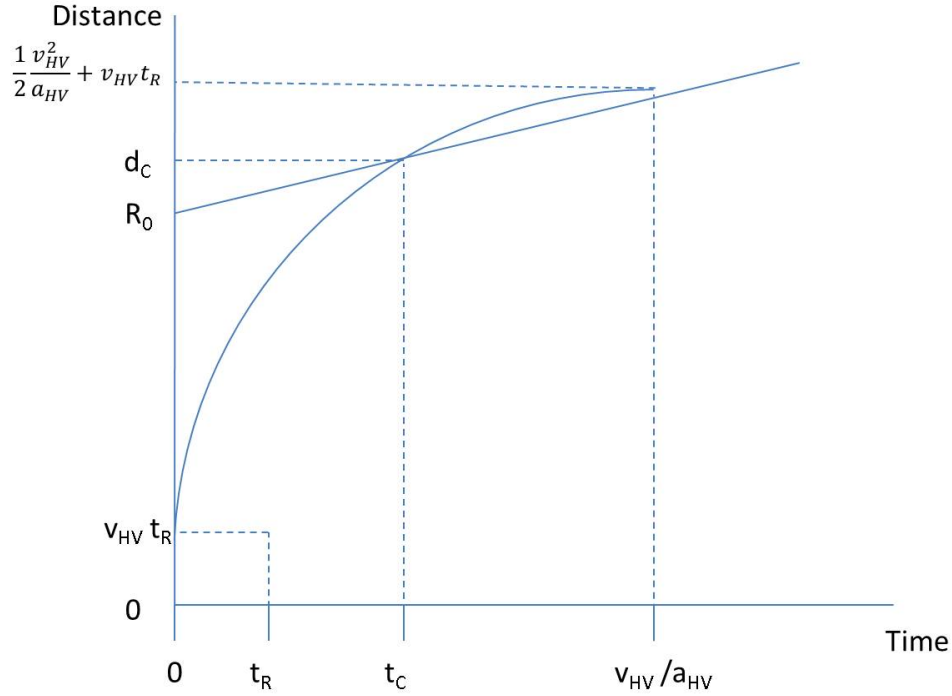
Figure 33. LVM Collision Distance Versus Time

At d_C, we have:

$$d_H = d_R \tag{64}$$

This condition is Equation (58) equal to Equation (63). Solving this equation for t_C yields:

$$t_C = \pm \sqrt{ -\frac{2}{a_{HV}}(R_0 - v_{HV}t_R) + \frac{(v_{HV-v_{RV}})^2}{a_{HV}{}^2} + \frac{(v_{HV} - v_{RV})}{a_{HV}} } \tag{65}$$

Substituting Equation (65) into Equation (62) and using Equation (61) yields Equation (66), the *LVM collision velocity*:

$$v_C = \sqrt{(v_{HV} - v_{RV})^2 - 2a_{HV}(R_0 - v_{HV}t_R)} \tag{66}$$

B.1.3 LVD Collision Velocity

The CF equation for the LVD collision velocity is derived in a similar manner as the LVM equation. The collision velocity is again given as Equation (61). The RV velocity now varies linearly with time and the HV velocity is given as Equation (56). Thus, at the collision time, t_C:

$$v_2 = -a_{RV}t_C + v_{RV} \quad \text{and} \quad v_1 = -a_{HV}t_C + v_{HV} \tag{67}$$

B-4

Since the RV velocity is now linear, the distance traveled is a quadratic function of time (see Figure 32 with HV now given by RV). Equation (68) gives the parabolic form of the distance d:

$$d_R = -\frac{1}{2} a_{RV}\, t^2 + v_{RV} t + R_0 \tag{68}$$

By completing the square, this can be rewritten:

$$d_R = -\frac{1}{2} a_{RV} \left(t - \frac{v_{RV}}{a_{RV}} \right)^2 + \frac{1}{2} \frac{v_{RV}^2}{a_{RV}} + R_0 \tag{69}$$

The intersection of the two curves d_R and d_H defines the collision time, t_C (see Figure 34).
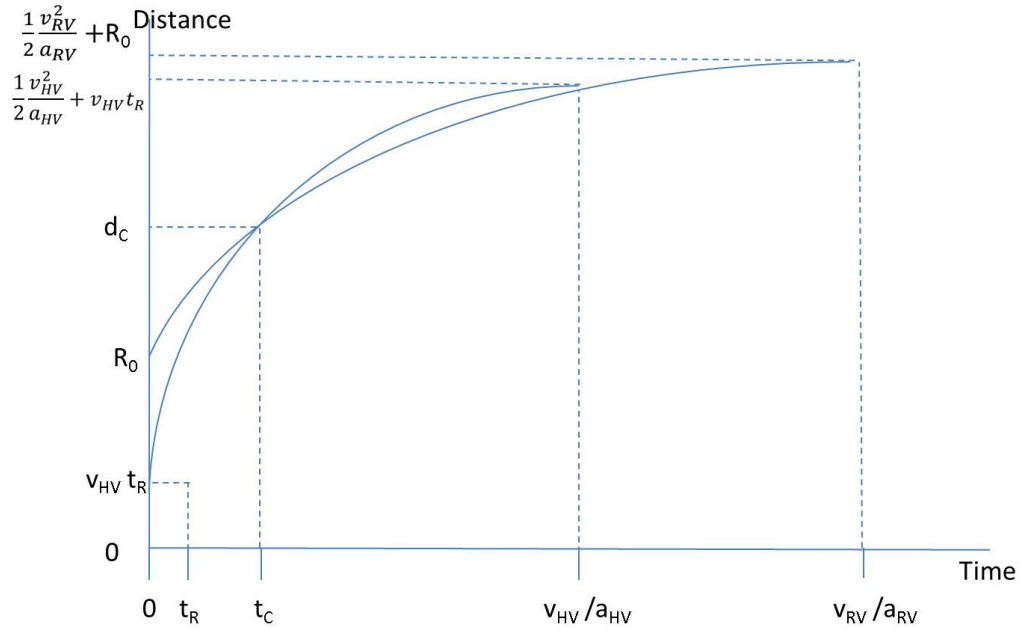

Figure 34. LVD Collision Distance Versus Time

At d_C, we have again Equation (64). This condition is Equation (58) set equal to Equation (69). Solving this equation for t_C yields:

$$t_C = \pm \sqrt{ -\frac{2}{(a_{HV} - a_{RV})}(R_0 - v_{HV} t_R) + \frac{(v_{HV} - v_{RV})^2}{(a_{HV} - a_{RV})^2} } + \frac{(v_{HV} - v_{RV})}{(a_{HV} - a_{RV})} \tag{70}$$

Substituting Equation (70) into Equation (67) and using Equation (61) yields Equation **(71)**, the *LVD collision velocity*:

$$v_C = \sqrt{(v_{HV} - v_{RV})^2 - 2(a_{HV} - a_{RV})(R_0 - v_{HV} t_R)} \tag{71}$$

B.2 Crossing Path Closed-Form Module

As in the numerical case, two distinct HV speed profiles were implemented:

1. SCP-M was modeled as an HV approaching an intersection at a constant, significant speed.
2. SCP-S was modeled as an HV approaching an intersection in a "creeping" motion while accelerating from an initial very low speed (i.e., from a stop).

In both cases above, the HV brakes if the HV driver reaction time has elapsed. The RV always initially moves at constant speed and brakes if the RV driver reaction time has elapsed.

If the HV driver reaction time, t_{RH}, is greater than TTI, then Equations (72) and (73) hold. The HV time to reach the conflict zone is:

$$TTRZ_{HV} = \frac{R_{HV}}{V_{HV}} \tag{72}$$

The HV time to clear the conflict zone is:

$$TTCZ_{HV} = \frac{R_{HV} + L_{HV} + W_{RV}}{V_{HV}} \tag{73}$$

In this case, v_{HV} depends on whether the HV is initially moving or stopped. For a moving HV, v_{HV} is simply the initial value. For a stopped HV, $v_{HV} = a_{H0}$ TTI (where a_{H0} is the initial acceleration).

If the HV reaction time is less than or equal to TTI, then Equations (74) and (75) hold.

The HV time to reach the conflict zone is:

$$TTRZ_{HV} = \left(\frac{-v_{HV} + \sqrt{v_{HV}^2 + 2a_H\, R_{HV}}}{a_H} \right) + t_{RH} \tag{74}$$

The HV time to clear the conflict zone is:

$$TTCZ_{HV} = \left(\frac{-v_{HV} + \sqrt{v_{HV}^2 + 2a_H\, (R_{HV} + L_{HV} + W_{RV})}}{a_H} \right) + t_{RH} \tag{75}$$

In this case, v_{HV} depends on whether the HV is initially moving or stopped:

- If the HV is moving, the speed at the conflict zone is:

$$v_{HV} = \sqrt{2a_H \left(\frac{1}{2} \frac{v_{HV}^2}{a_H} + v_{HV} t_{RH} - R_{HV} \right)} \tag{76}$$

- If the HV is stopped, the speed at the conflict zone is:

$$v_{HV} = \sqrt{2a_H \left(\frac{1}{2}\frac{v_{HV}^2}{a_H} + \frac{1}{2}a_{H0}t_{RH}^2 - R_{HV}\right)} \tag{77}$$

If the RV driver reaction time, $t_{R_{RV}}$, is greater than TTI, then Equations (78) and (79) hold:

The RV time to reach the conflict zone is:

$$TTRZ_{RV} = \frac{R_{RV}}{V_{RV}} \tag{78}$$

The RV time to clear the conflict zone is:

$$TTCZ_{RV} = \frac{R_{RV} + L_{RV} + W_{HV}}{V_{RV}} \tag{79}$$

In this case, v_{RV} is the constant initial value.

If the RV driver reaction time, $t_{R_{RV}}$, is less than or equal to TTI, then Equations (80) and (81) hold.

The RV time to reach the conflict zone is:

$$TTRZ_{RV} = \left(\frac{-v_{RV} + \sqrt{v_{RV}^2 + 2a_R R_{RV}}}{a_R}\right) + t_{RR} \tag{80}$$

The RV time to clear the conflict zone is:

$$TTCZ_{RV} = \left(\frac{-v_{RV} + \sqrt{v_{RV}^2 + 2a_R (R_{RV} + L_{RV} + W_{HV})}}{a_R}\right) + t_{RR} \tag{81}$$

In this case, the new speed is:

$$v_{RV} = \sqrt{2a_R \left(\frac{1}{2}\frac{v_{RV}^2}{a_R} + v_{RV}t_{RR} - R_{RV}\right)} \tag{82}$$

There are two crash cases:

1. *HV enters conflict zone first*: when the HV enters the conflict zone first, the following holds:

$$TTRZ_{HV} < TTRZ_{RV} \tag{83}$$

For a crash to occur in these circumstances, the RV must reach the conflict zone before the HV exits it. This occurs when:

$$TTRZ_{RV} < TTCZ_{HV} \tag{84}$$

The RV impacts the HV when both these conditions hold:

$$TTRZ_{HV} < TTRZ_{RV} < TTCZ_{HV} \tag{85}$$

2. *RV enters conflict zone first*: in a parallel development, it can be shown that the HV impacts the RV when this condition holds:

$$TTRZ_{RV} < TTRZ_{HV} < TTCZ_{RV} \tag{86}$$

There are four crash avoidance cases:

1. *HV or RV stops before conflict zone*: either the HV or the RV stops before entering the intersection. Because each vehicle has an initial speed, drivers must brake to stop before entering the intersection. Here, the focus is the HV. For an initially moving HV, decelerating at level a_H, if the brakes are fully activated at the distance R_{HV} from the conflict zone, a crash is avoided when the following condition holds:

$$\frac{v_{HV}^2}{2a_H} + v_{HV}t_{RH} < R_{HV} \tag{87}$$

Or, if the HV is initially stopped:

$$\frac{v_{HV}^2}{2a_H} + \frac{1}{2}a_{H0}t^2{}_{RH} < R_{HV} \tag{88}$$

2. A similar result applies to the RV:

$$\frac{v_{RV}^2}{2a_R} + v_{RV}t_{RR} < R_{RV} \tag{89}$$

3. *RV enters conflict zone after HV exits*: the HV enters and exits the conflict zone before the RV reaches it. Once the HV exits the conflict zone, the zone is no longer defined. Mathematically, the following holds when the HV exits the conflict zone before the RV enters it:

$$TTCZ_{HV} < TTRZ_{RV} \tag{90}$$

4. *HV enters conflict zone after RV exits*: in a parallel development, this equations shows that the RV exits the conflict zone before the HV reaches it when:

$$TTCZ_{RV} < TTRZ_{HV} \tag{91}$$

If any of the four crash avoidance cases are true, then the simulation run does not have a crash. If all four crash avoidance cases are false, then a crash has occurred, and the appropriate crash speed is assigned as in the numerical case: if the RV impacts the HV, then the collision speed is given by the RV speed; and if the HV impacts the RV, then the collision speed is given by the HV speed.

The resulting impact mode depends on 1) which direction the RV enters the intersection and 2) the impacting vehicle:

- If the RV is entering from the right and the <u>RV impacts the HV</u>, then the impact is right-to-front.
- If the RV is entering from the right and the <u>HV impacts the RV</u>, then the impact is front-to-left.
- If the RV is entering from the left and the <u>RV impacts the HV</u>, then the impact is left-to-front.
- If the RV is entering from the left and the <u>HV impacts the RV</u>, then the impact is front-to-right.

B.3   Lane Change Closed-Form Module

The lane-change closed form conflict analysis begins as the HV is placed at an initial lateral distance away from the RV, $R_{initial}$. The value $R_{initial}$ is obtained by adding the user-specified RV initial distance to lane marker, RRV, and the HV initial distance to lane marker, RHV. The longitudinal speed of both vehicles is the same and thus the computation is reduced to one dimension – the lateral motion of the HV. The lateral velocity of the HV at a time t after the reaction time t_R is given by Equation (92):

$$v = v_0 + a_0(t + t_R) + \frac{1}{2}j_0 t_R{}^2 - \frac{1}{2}j_R t^2 \tag{92}$$

When $v = 0$, the HV has stopped moving toward the RV; for this case, the time t is given by Equation (93):

$$t = \frac{a_0}{j_R} + \frac{\sqrt{a_0^2 + 2j_R(v_0 + a_0 t_R + \frac{1}{2}j_0 t_R{}^2)}}{j_R} \tag{93}$$

The distance traveled after coming to a stop is given by Equation (94):

$$d = \frac{1}{2}j_0 t_R{}^2(t + t_R) + \frac{1}{2}a_0(t + t_R)^2 + v_0(t + t_R) \\ - \frac{1}{6}j_R(t - t_R)^3 \tag{94}$$

When d is less than $R_{initial}$, there is no collision. Otherwise, we search and loop Equation (94) over t for the time when d is equal to $R_{initial}$. At this condition, the velocity at impact is given as Equation (92).

Appendix C: Lane Change Motion Validation

The LC kinematic module was developed to mimic the natural motion of a lane change maneuver under normal driving conditions. The natural motion of a vehicle in a lane change maneuver was determined from the IVBSS field test data. Valid baseline and treatment alerts, and driver responses, for the IVBSS lane change warning system were analyzed. Basic measures of lateral distance, lateral speed, and lateral acceleration were examined. Figure 35 shows an example time series plot of lateral acceleration in a lane change maneuver with a warning and counter steer response.
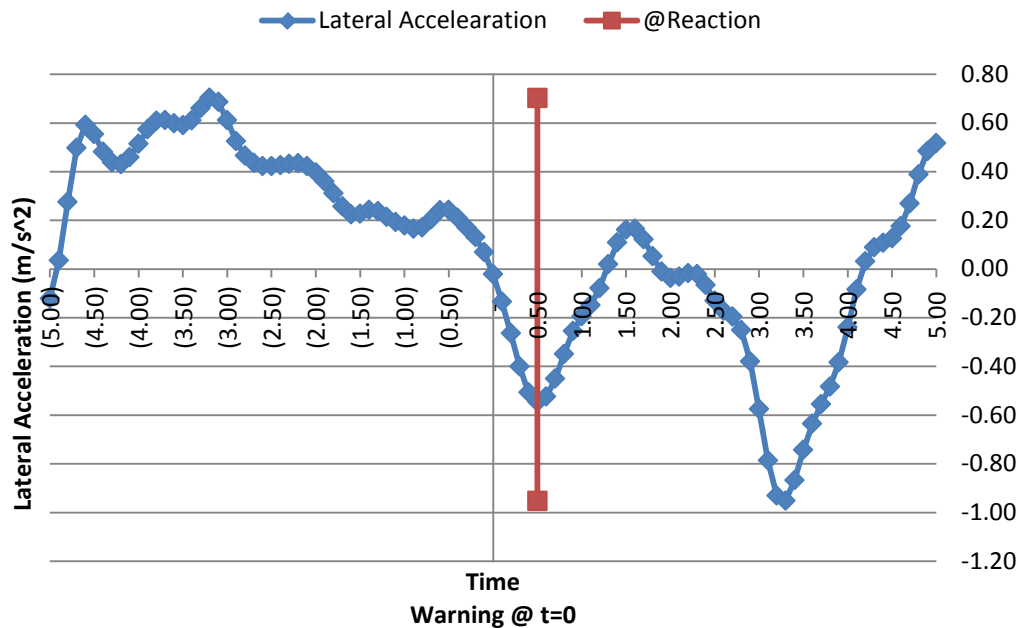

Figure 35. Example Lateral Acceleration Plot for Valid Lane Change Alert and Driver Response

As seen in the figure, the lateral acceleration exhibits a steady change from 0.75 seconds before the warning (when the driver initiates the lane change). This steady change is seen until a peak, 0.5 seconds after the warning, when the driver reacts and begins counter steer (this can be seen as the driver reaction time). A steady change is seen in the counter steer response until the driver returns to the original lane and then ultimately initiates the lane change again when no conflict is present. It was determined that a change in lateral acceleration was needed, which is reflected in the governing equations in Section 3.1, Equations (4) through (7). The j term, also known as a "jerk," is the change in acceleration over a given time, t.

DOT HS 812 890
May 2021

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